Mitigation of irregular respiration in 4DCT

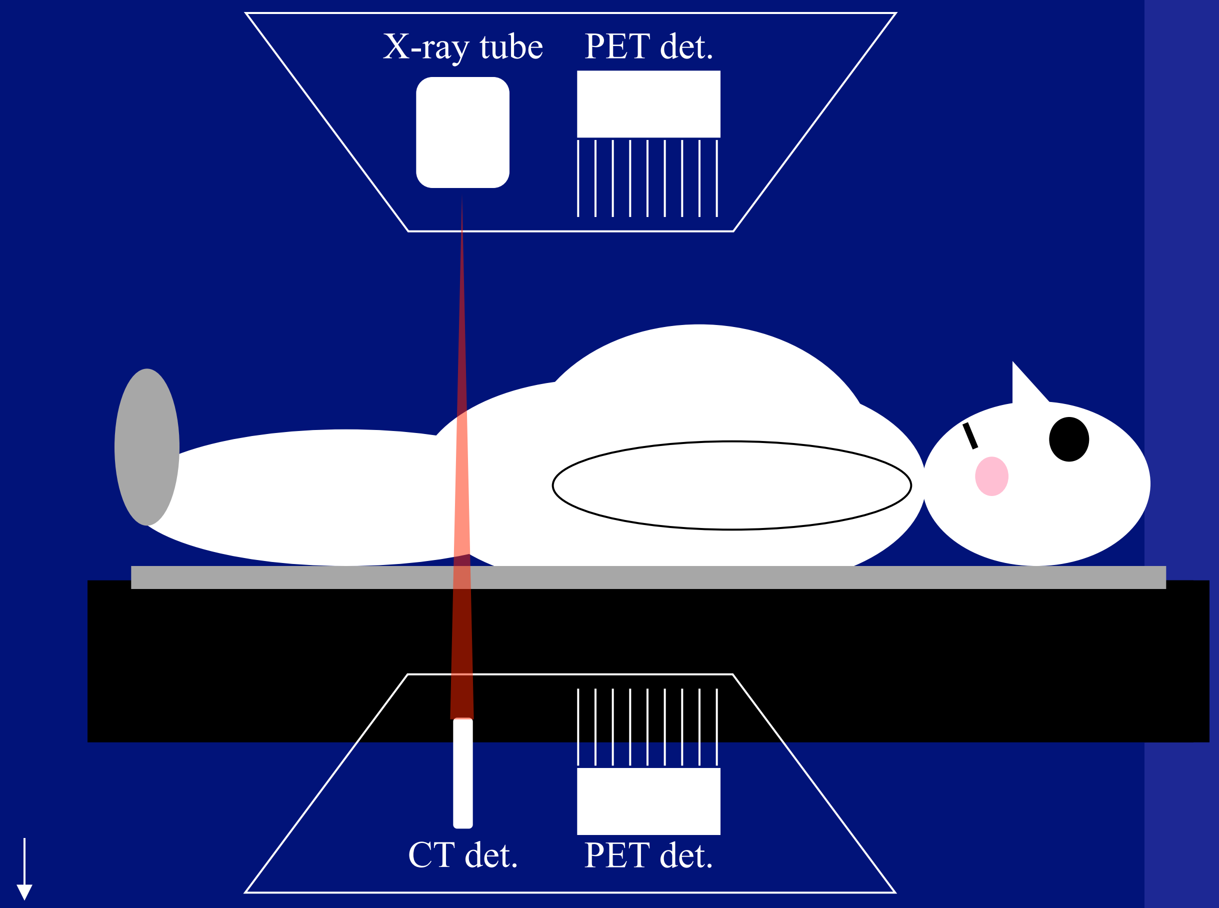
Tinsu Pan, Ph.D.

M.D. Anderson Cancer Center
The University of Texas

Outlines

- Introduction to 4D-CT
- Data sufficiency condition
- Artifacts
- Integration with PET/CT
- Mitigation of irregular respiration in 4D-CT
- Radiation to implantable cardiac devices
- Summary

Helical CT data acquisition



Breathing artifacts

16x0.625 mm, 0.8 s gantry rotation, pitch 1.375:1, speed: 17.2 mm/s

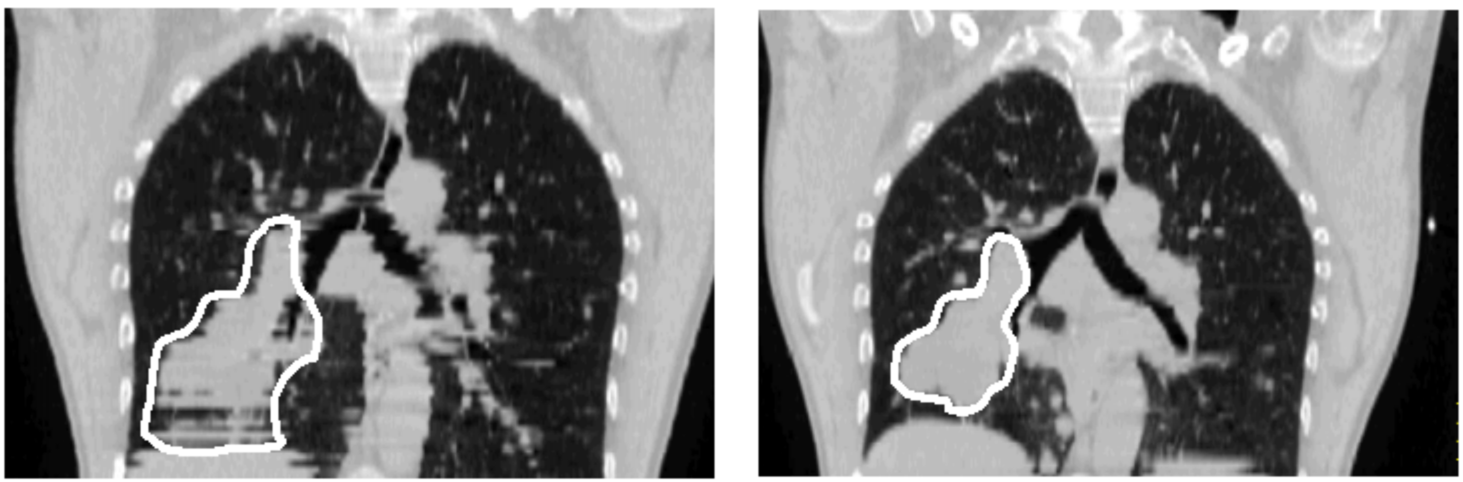
First 4D-CT

Potential radiotherapy improvements with respiratory gating

P. J. Keall[1], V. R. Kini[1], S. S. Vedam[2], and R. Mohan[1]

[1]*Department of Radiation Oncology*
[2]*Departments of Biomedical Engineering and Radiation Oncology Virginia Commonwealth University Health System*

Australas. Phys. Eng. Sci. Med. Vol. 25, No 1, 2002



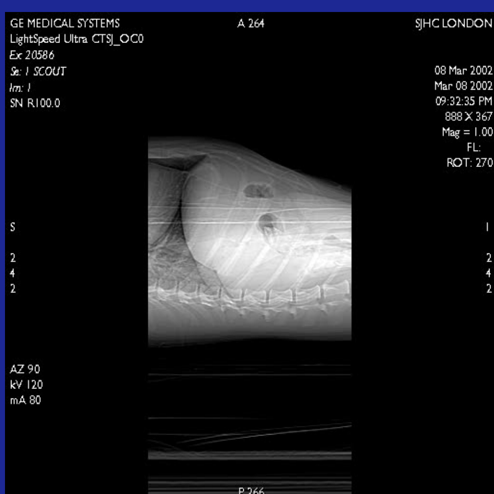
a) b)

Figure 1. *A coronal view of CT scans of the same patient taken (a) without gating and (b) with gating at exhale. The gross tumour volume (GTV) is outlined in each image.*

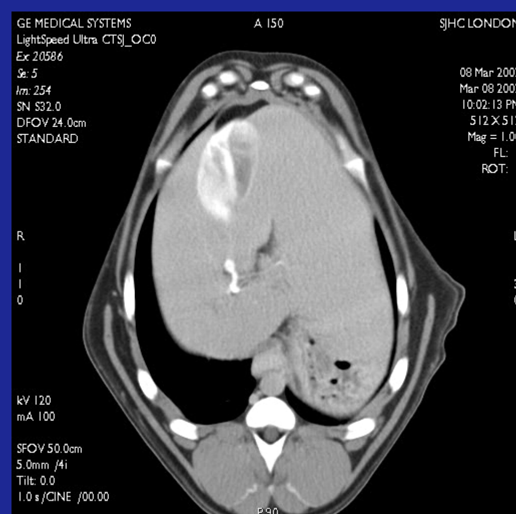
Philips single slice PQ 5000 CT scanner, 3 mm slice, single phase gating > 8 min, end-inspiration h/w gating

1st GE 4D-CT (March 8, 2002)

Animal setup



Scout view



Axial view plus time

6 cm

Coronal view plus time

Pan, et al, Med Phys '04

Early 4D-CT work

Scanner	Slices (mm)	GC (s)	Acq.	Pitch	Speed (mm/s)	Image Gap	Acq. Time
Phillips 1-slice [1]	3	1.0	Cine	N/A	0.5	None	420 sec
Phillips 1-slice[2,3]	3	1.5	Helical	0.5	1	Yes	200 sec
Siemens 4-slice [4]	4 x 2.5	0.75	Cine	N/A	0.8	None	251 sec
GE 4-slice [5]	4 x 2.5	0.5	Cine	N/A	1.6	None	126 sec
GE 8-slice [5]	8 x 2.5	0.5	Cine	N/A	3.2	None	63 sec
Philips 16-slice [6]	16 x 1.75	0.5	Helical	0.125	6	Yes	50 sec

1. **Keall et al, *Phys. Eng. Sci. Med., 2002.***
2. **Vedam et al, *Phys. Med. Biol., 2003.***
3. **Ford et al, *Med. Phys., 2003.***
4. **Low et al, *Med. Phys., 2003.***
5. **Pan et al, *Med. Phys., 2004.***
6. ***Keall et al, PMB, 2004.***

All 4D-CT assume regular breathing. MSCT made 4D imaging practical.

CT scan modes

Step and shoot	Step and shoot (cardiac, calcium scoring)	Cine (4DCT)
One rotation (≤ 4 s) per position	X-ray on for 240 degrees	Multiple rotations per step
Helical	Helical (cardiac)	Helical (4DCT)
pitch 0.5 to 1.5	pitch 0.2 to 0.3	pitch < 0.1

$$\text{pitch} = \frac{\text{table translation per rotation}}{\text{X-ray beam width}}$$

Data Sufficiency Condition

- Per location the acquisition time has to be at least
  - average breathing cycle T_b, plus
  - data acquisition for an image reconstruction T_g

- Cine acquisition ($T_b = 4$ s, $T_g = 0.5$ s)
  - 4.5 s per cine step

- Helical acquisition ($T_b = 4$ s, $T_g = 0.5$ s)
  - $P = T_g / (T_b + T_g)$ $\quad$ $P = 0.11$ @ 4 s

Longer breath cycle requires longer cine scan or smaller pitch helical scan

Cine 4D-CT Protocol

- 4 or 8 slices of 2.5 mm per rotation
- 0.5 sec or 0.8 sec/revolution
- Scan duration = breathing cycle + 1 sec
- Ensure the RPM is recording the respiratory waveform after the scout scan
- Push the scan button
- Dose is < 50 mGy for chest and < 75-100 mGy for abdomen

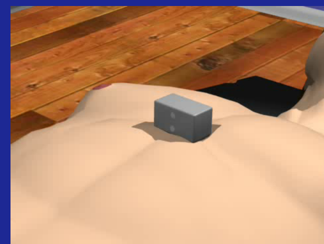
Helical 4D-CT Pitch Design

T_b	Siemens Design	
	p @ T_g=0.5	p @ T_g=1.0
3	0.1	N/A
4	0.1	N/A
5	0.1	N/A
6	N/A	0.1

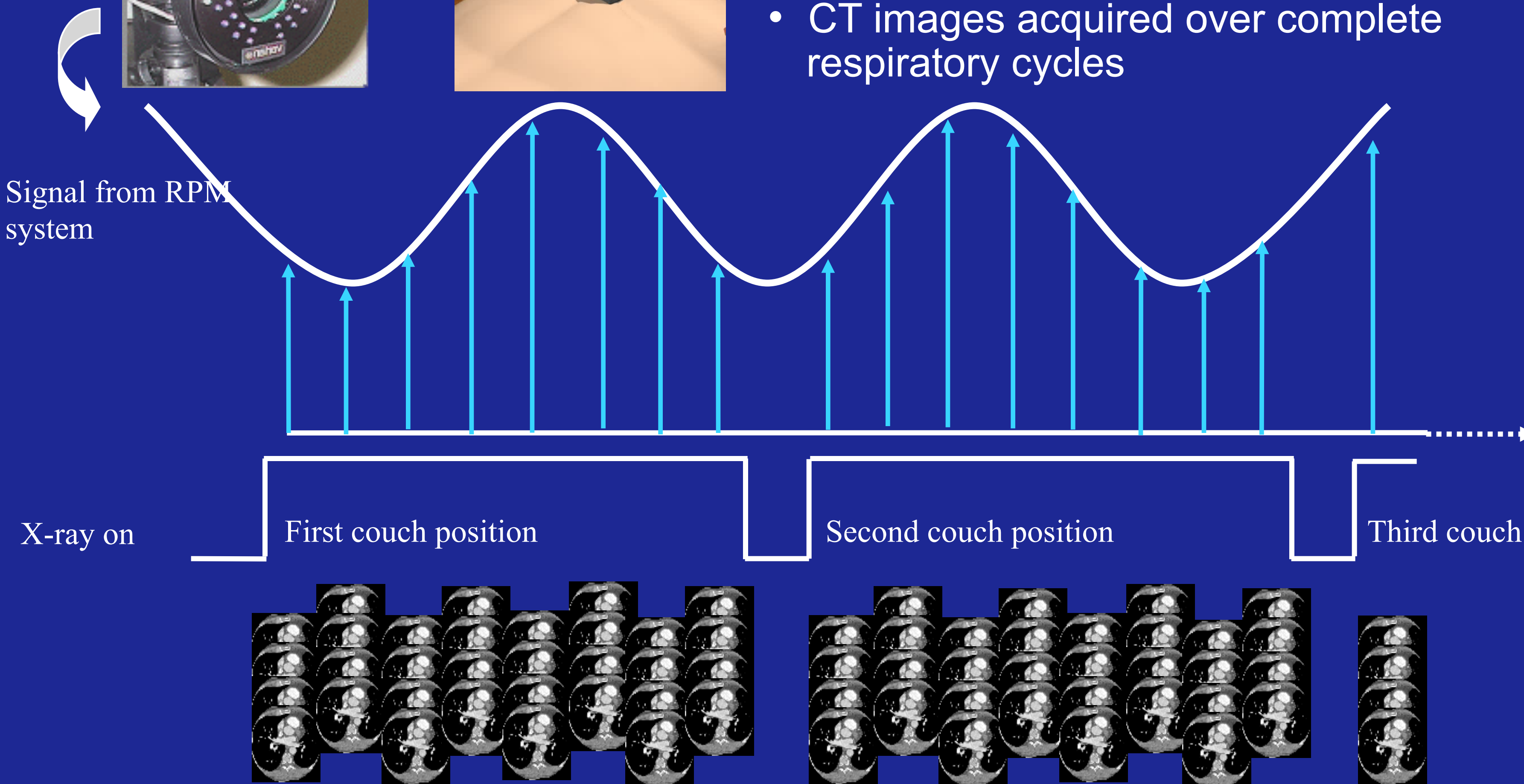
T_b	Philips Design	
	p @ T_g=0.5	p @ T_g=0.44
3	0.15	0.12
4	0.11	0.10
5	0.09	0.08
6	0.075	0.065

Longer breath cycle requires longer cine scan or smaller pitch helical scan

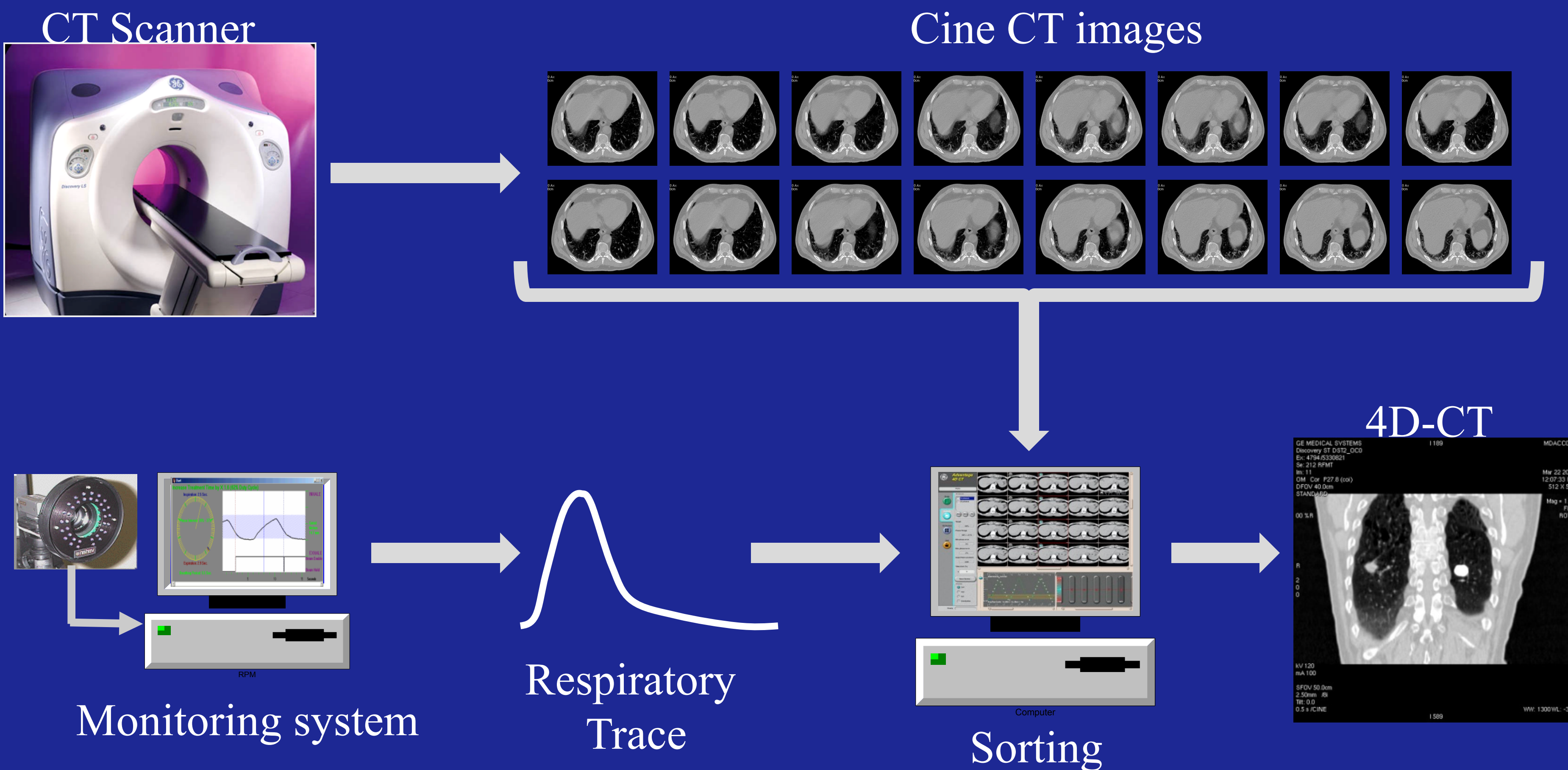
First commercial cine 4D-CT



- Respiratory tracking with Varian RPM optical monitor
- CT images acquired over complete respiratory cycles



Pan, et al, Med Phys '04



Pan, et al, Med Phys '04

Motion phantom experiment

4 sec cycle and 2 cm peak to peak motion

Pan et al, Med Phys, '04

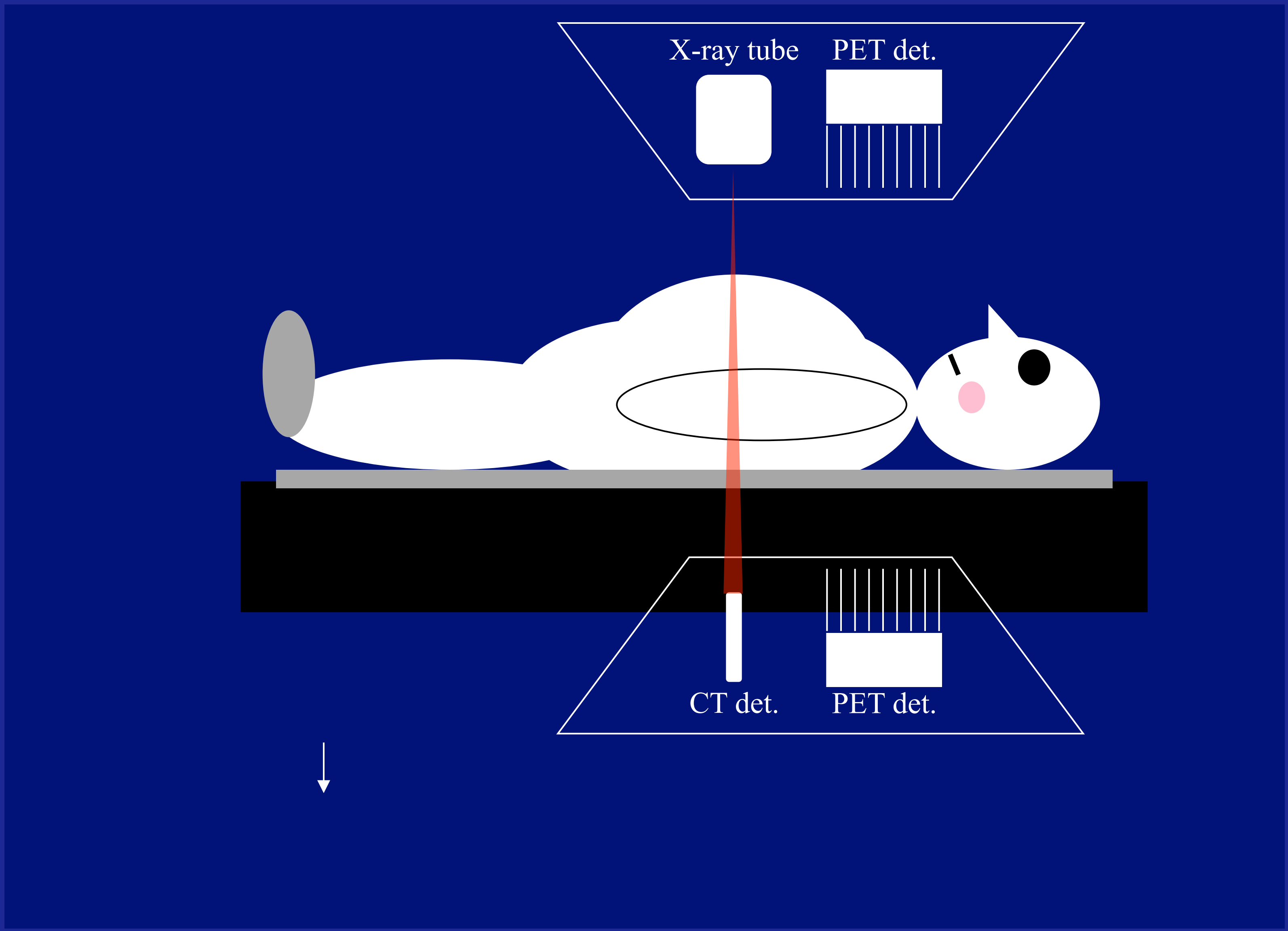
Effect of gating on phantom imaging

Helical CT

4D CT

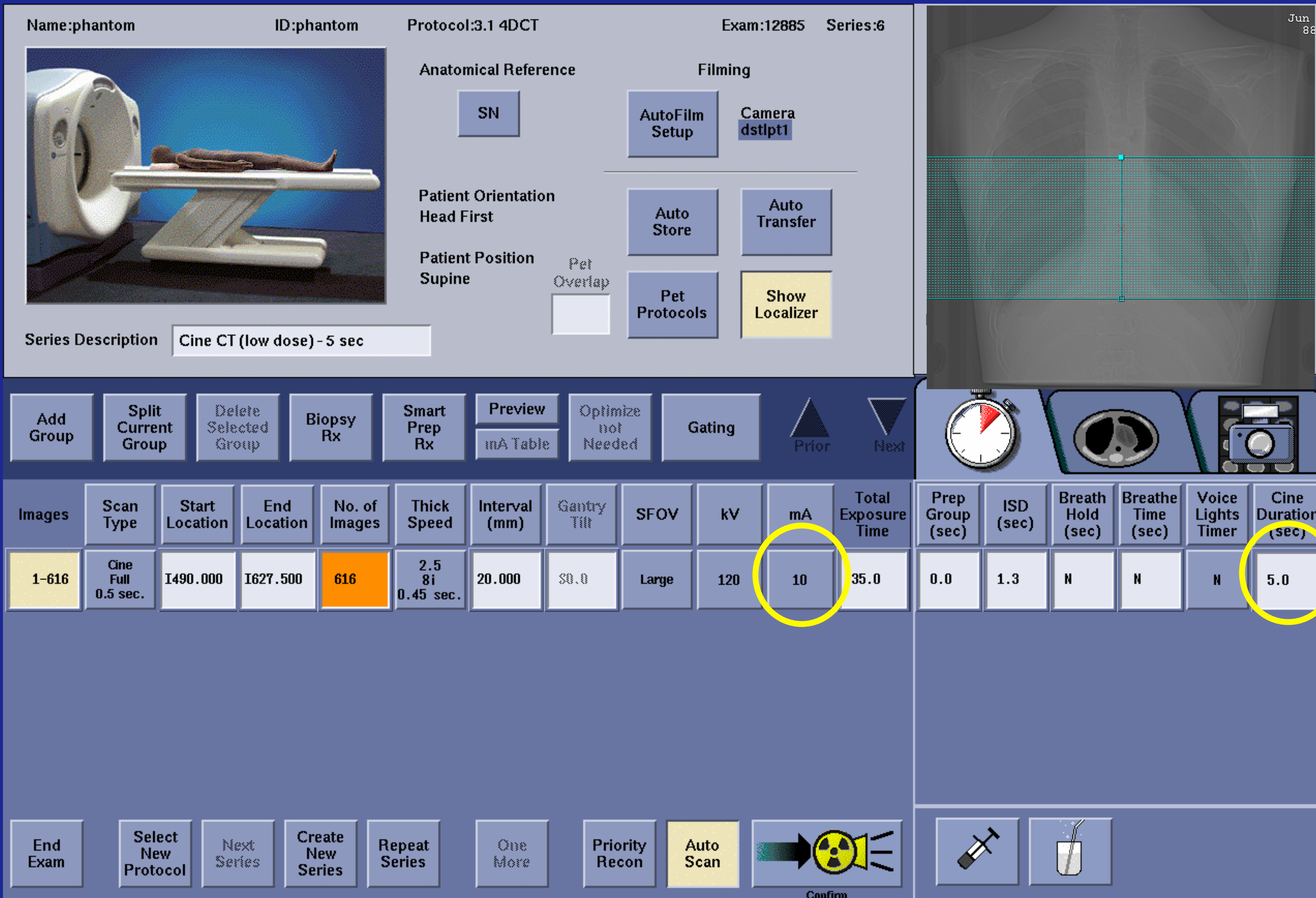
Gating preserves the shape and size of the object

Cine CT Data Acquisition

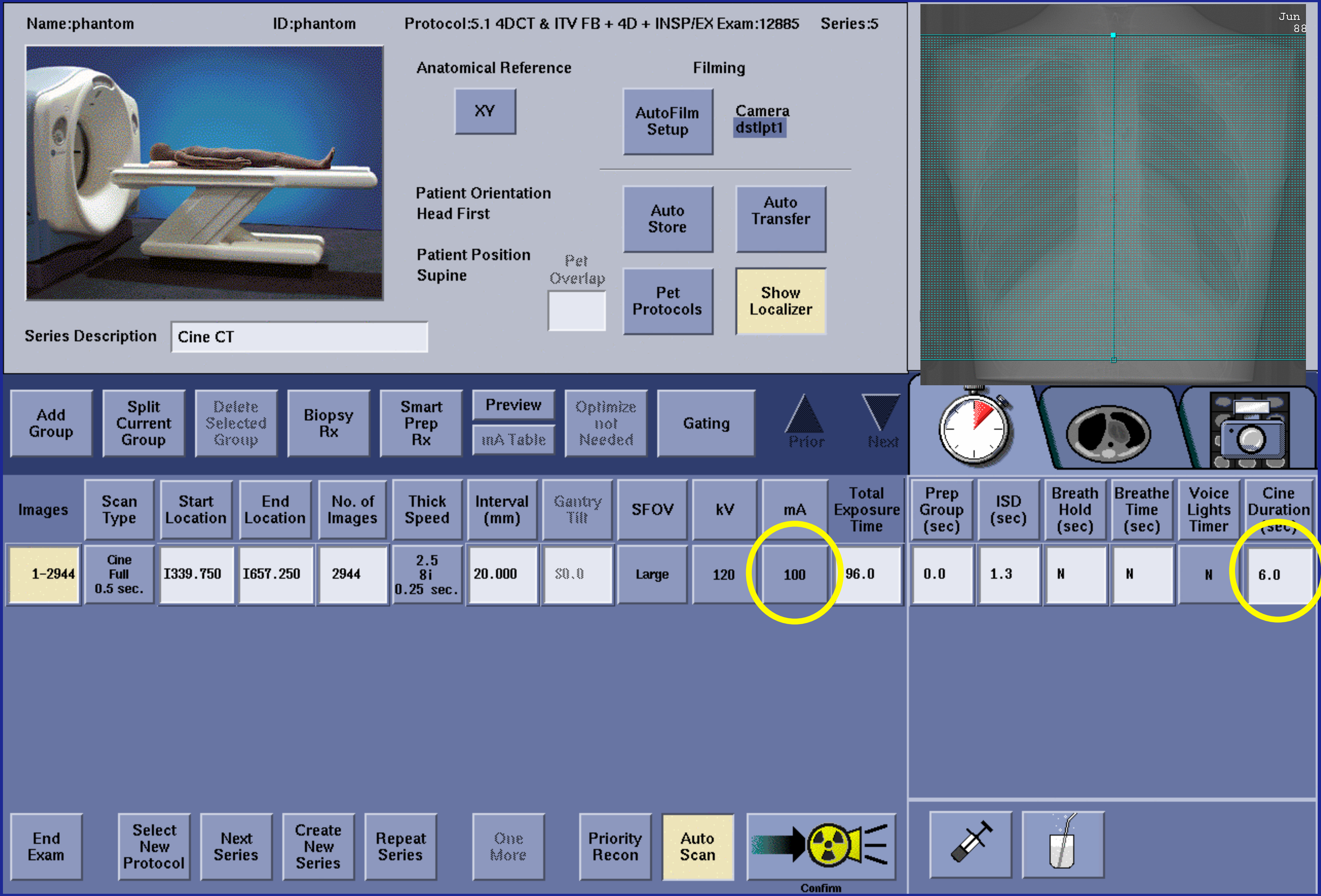


Pan et al, JNM, '04

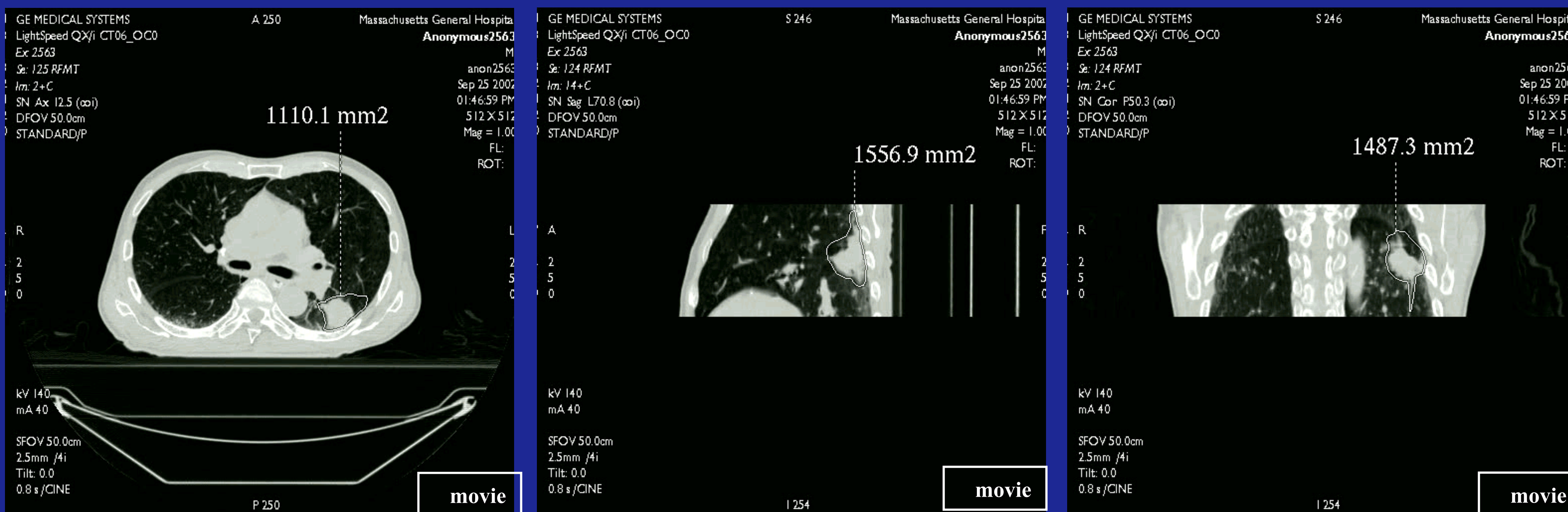
Cine CT user interface for low dose



Cine CT user interface for RT



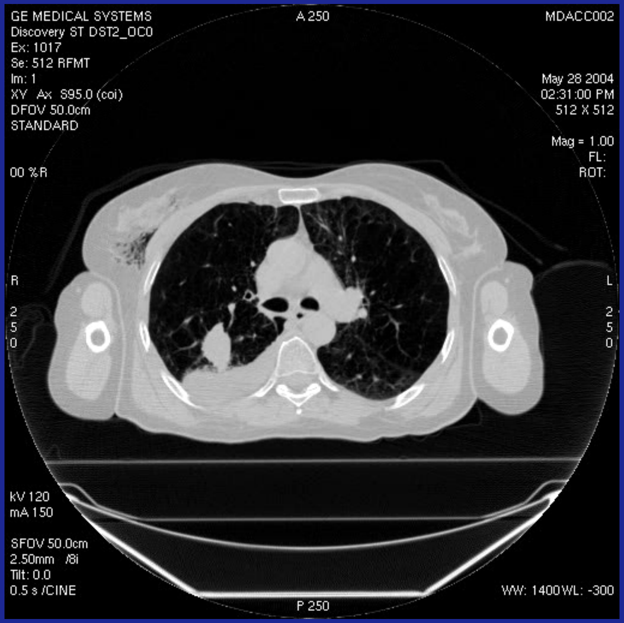
1st clinical case from MGH

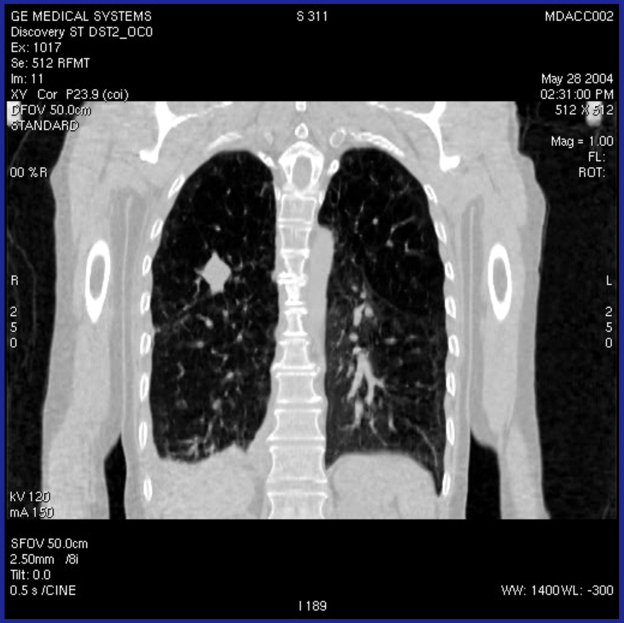


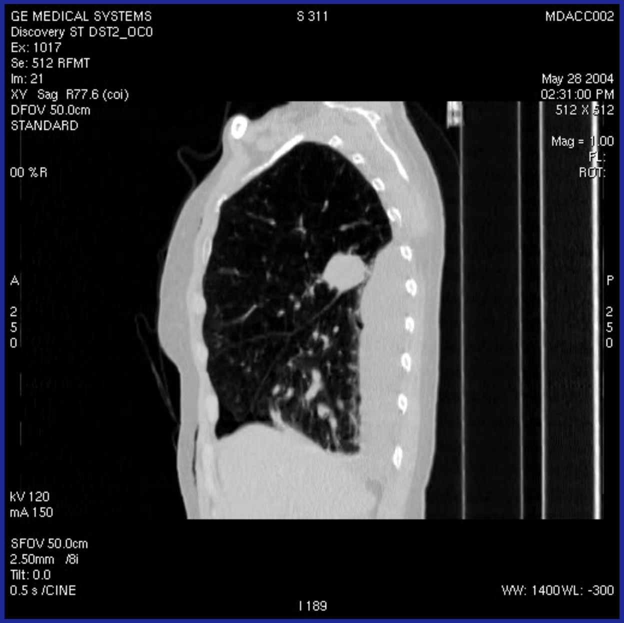
55 sec Cine scan (200 mAs sec per step) with free breathing of 3.72 sec average breathing cycle

Pan et al, Med Phys, 04

4D-CT patient study







4D-CT patient study with contrast

Int. J. Radiation Oncology Biol. Phys., Vol. 68, No. 2, pp. 531–540, 200

0360-3016/07/$–see front matte

ELSEVIER

doi:10.1016/j.ijrobp.2006.12.066

PHYSICS CONTRIBUTION

ASSESSING RESPIRATION-INDUCED TUMOR MOTION AND INTERNAL TARGET VOLUME USING FOUR-DIMENSIONAL COMPUTED TOMOGRAPHY FOR RADIOTHERAPY OF LUNG CANCER

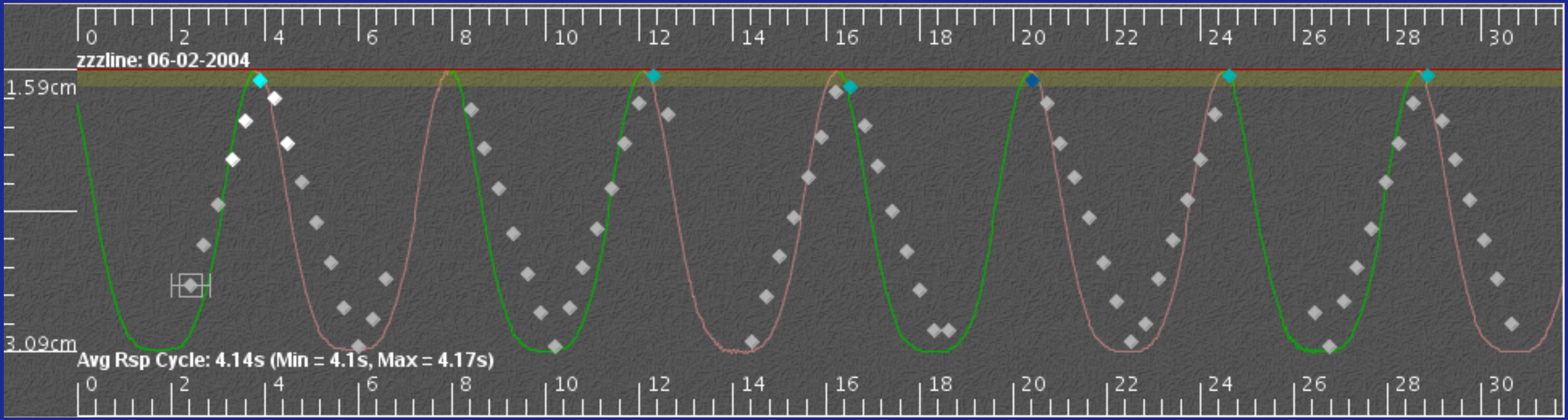
H. Helen Liu, Ph.D.* Peter Balter, Ph.D.,* Teresa Tutt,* Bum Choi, Ph.D.,* Joy Zhang, Ph.D.,* Catherine Wang, Ph.D.,* Melinda Chi, M.S.,* Dershan Luo, Ph.D.,* Tinsu Pan, Ph.D.,* Sandeep Hunjan, Ph.D.,* George Starkschall, Ph.D.,* Isaac Rosen, Ph.D.,* Karl Prado, Ph.D.,* Zhongxing Liao, M.D.,† Joe Chang, M.D., Ph.D.,† Ritsuko Komaki, M.D.,† James D. Cox, M.D.,† Radhe Mohan, Ph.D.,* and Lei Dong, Ph.D.*

Departments of *Radiation Physics and †Radiation Oncology, The University of Texas M. D. Anderson Cancer Center, Houston, TX

- 166 tumors in 152 patients
- 57.2% stage III & VI
- 10.8% > 1 cm

Artifacts

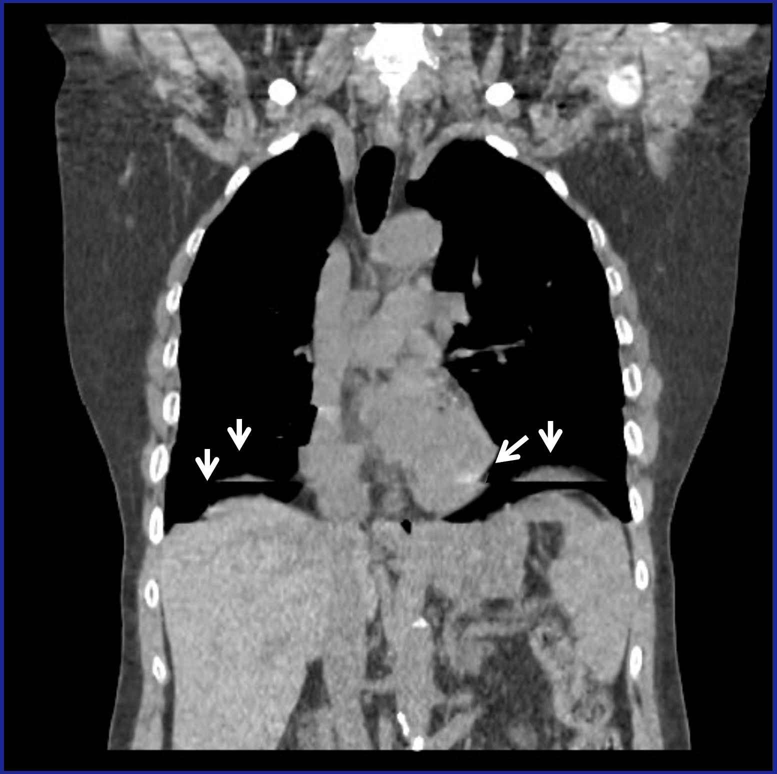
Ideal waveforms from RPM



No one is like this!

Basic assumptions of 4D-CT

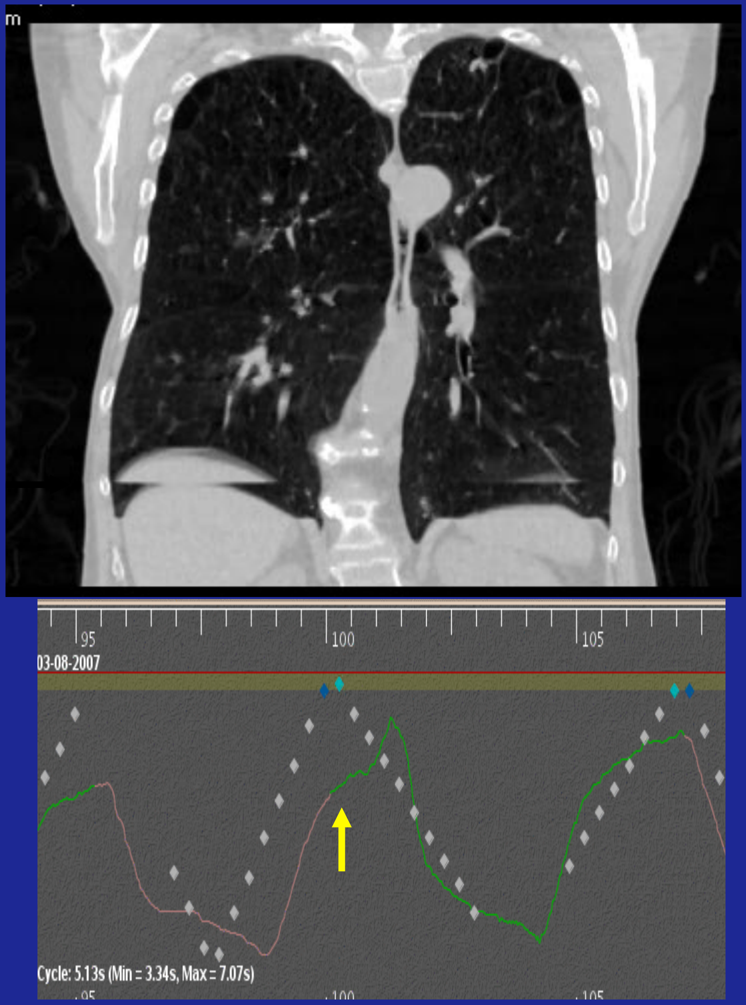
- Data acquisition for one breathing cycle per table position
- Over a couple of minutes to 4D-CT the whole lung



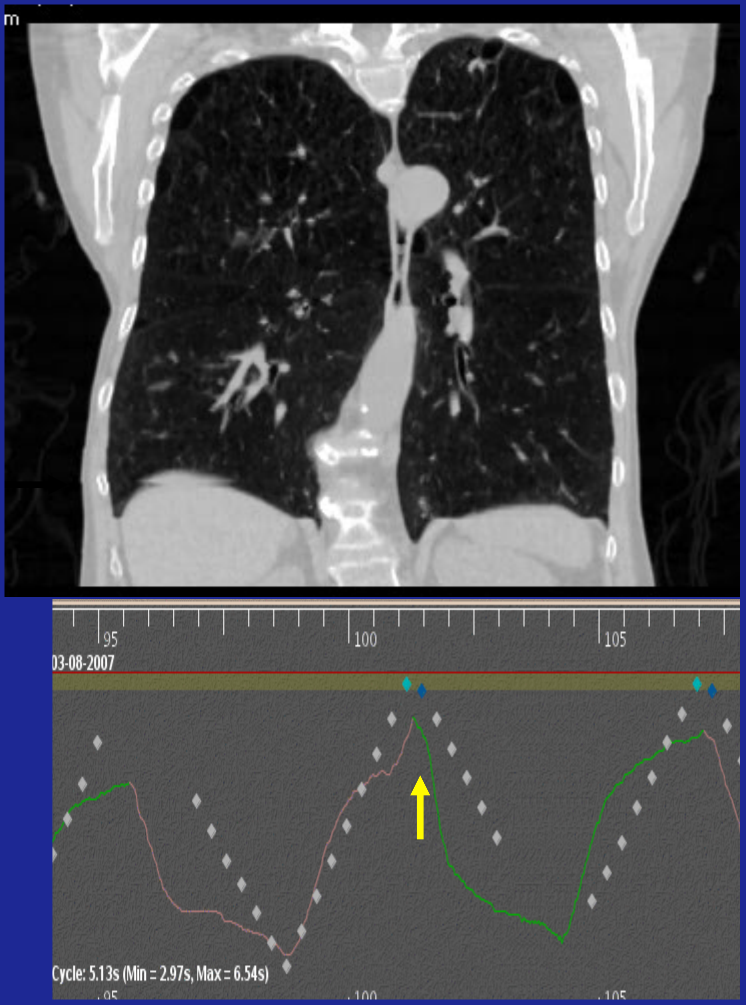
Irregular breathing

Undersampling

Ensure phase correctness



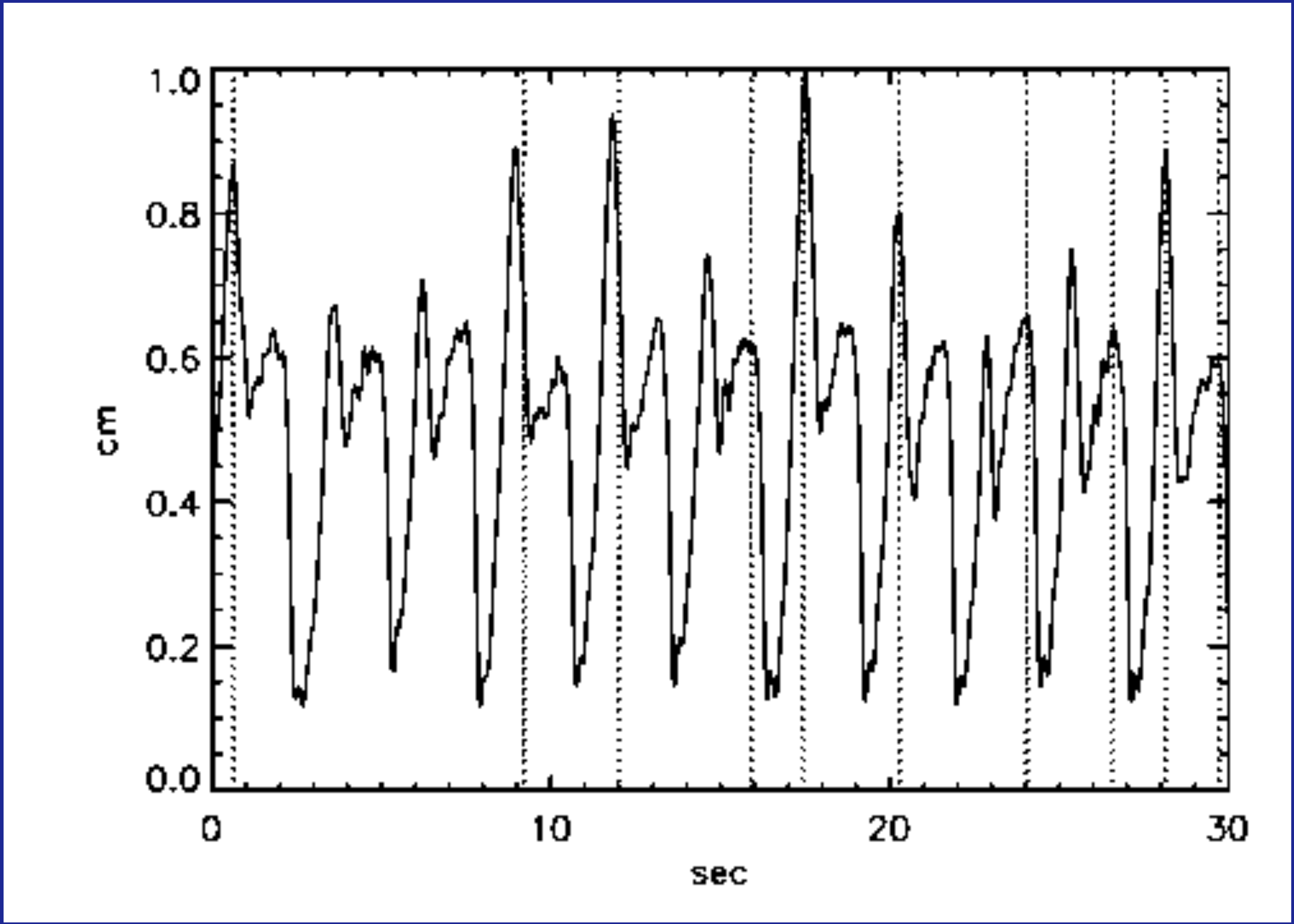
Incorrect EOI phase



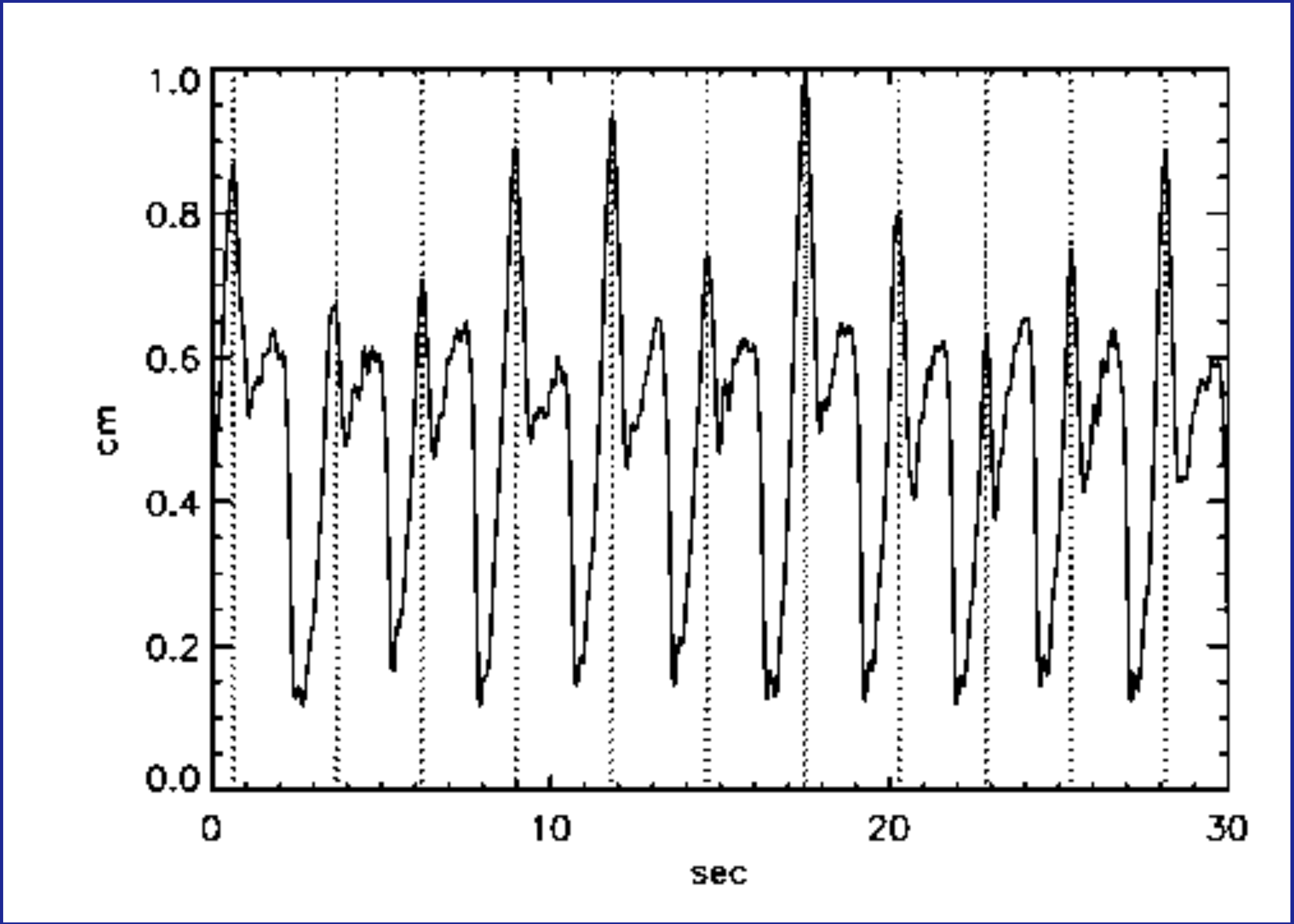
Correct EOI phase

Pan et al, Med Phys, '07

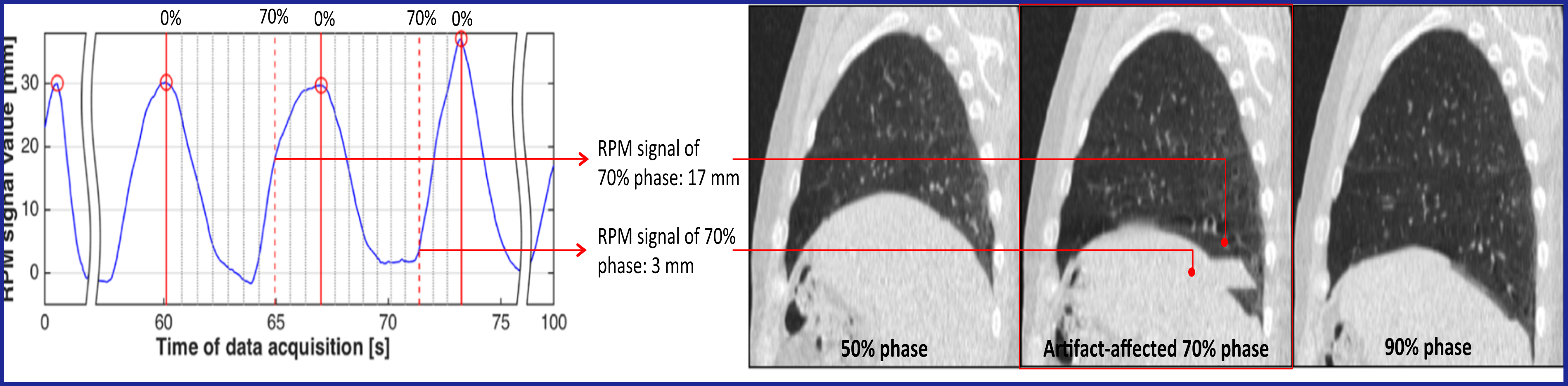
Incorrect ID of end-inspiration phases



Correct ID of end-inspiration phases



4D-CT (phase sorting issue)

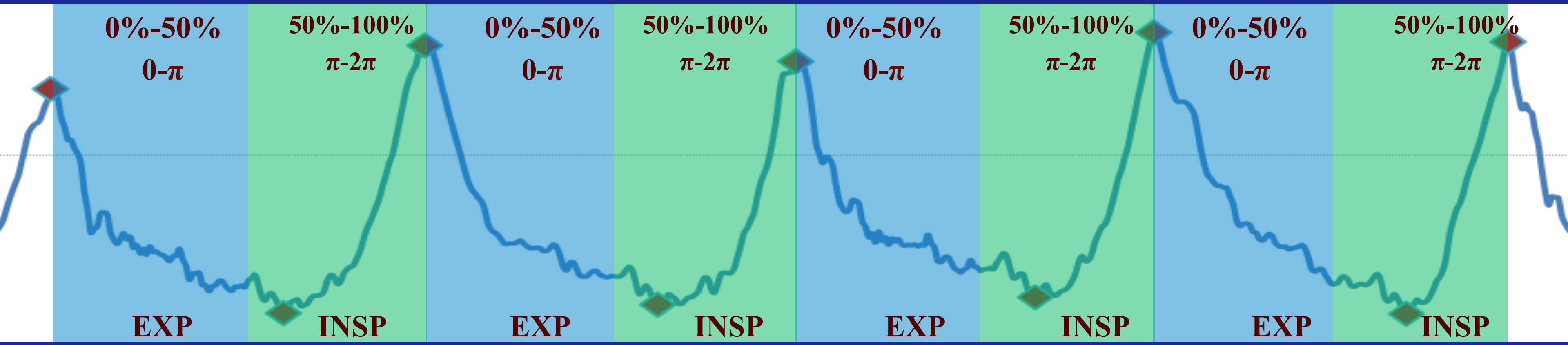


Artifact caused by Irregular respiration

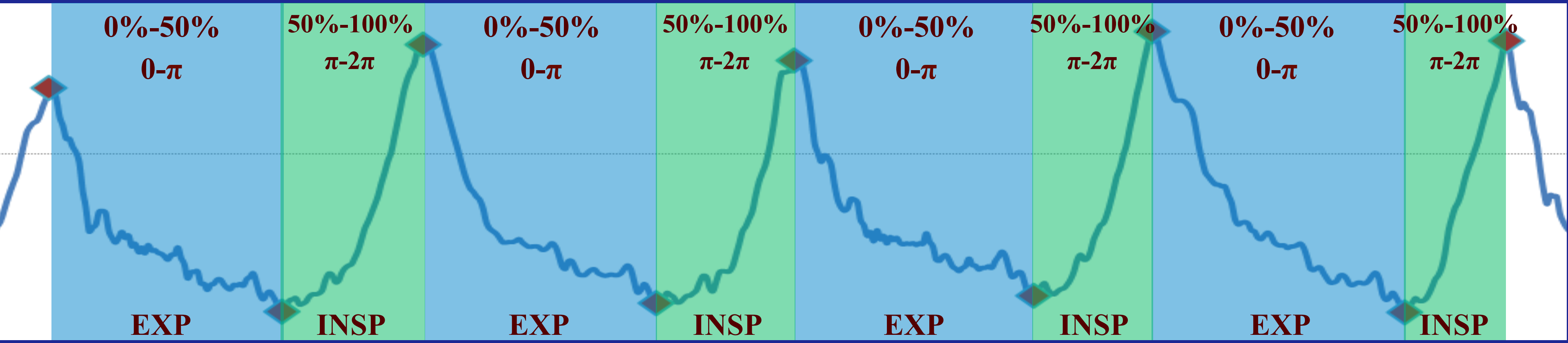
Werner et al, Radiation Oncology, '17

4D-CT

Conventional phase sorting



Phase corrected phase sorting



The contours in MIP may become smaller with phase correction.

Zamora et al, Med Phys, '10

Solutions for mitigating artifacts

- Patient experience the same short sessions of imaging and treatment for patient comfort

- Acquisition of more than 1 respiratory cycle
  - Additional time for data selection

- Repeat acquisition of the positions with irregular respiration
  - Additional tool for merging the data of regular respiration

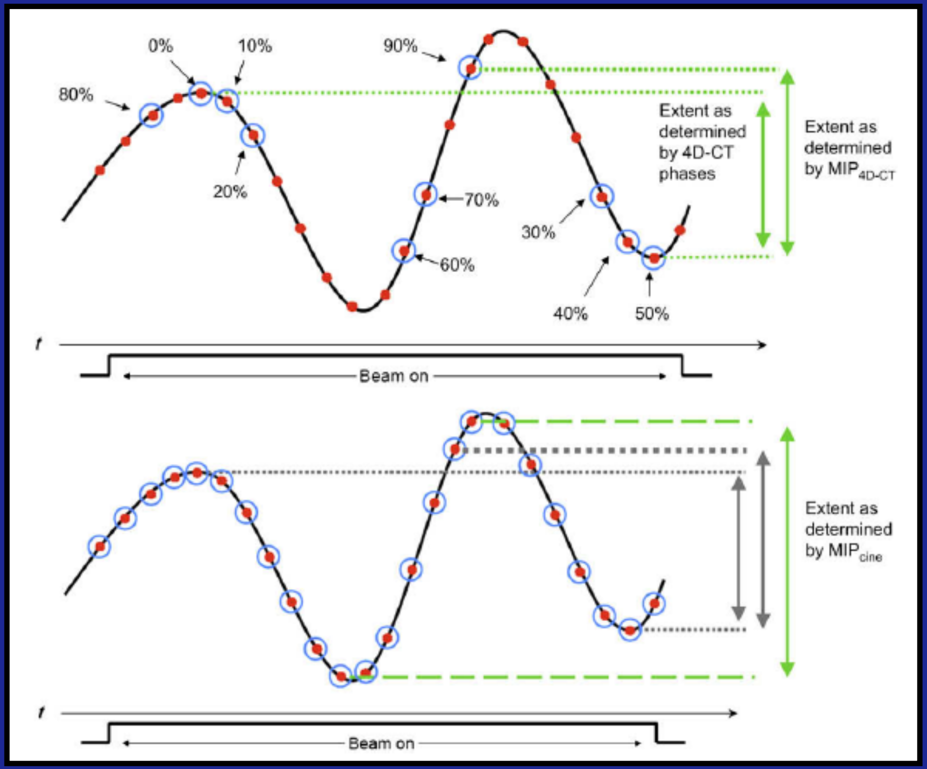
- Repeat the 4DCT study
  - Most used w/o guarantee the repeat scan is better than the first scan

- Prospective gating, i.e., acquisition of only the regular data
  - Proof of concept by Keall et al in 2007

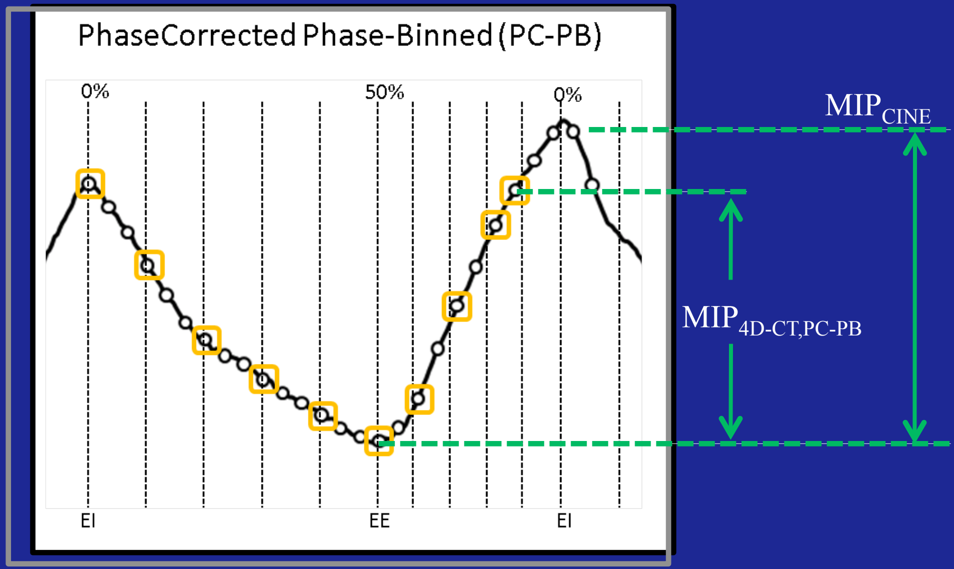
Two back to back 4D-CTs

Image quality degraded in long imaging session

Use the whole image data set for MIP

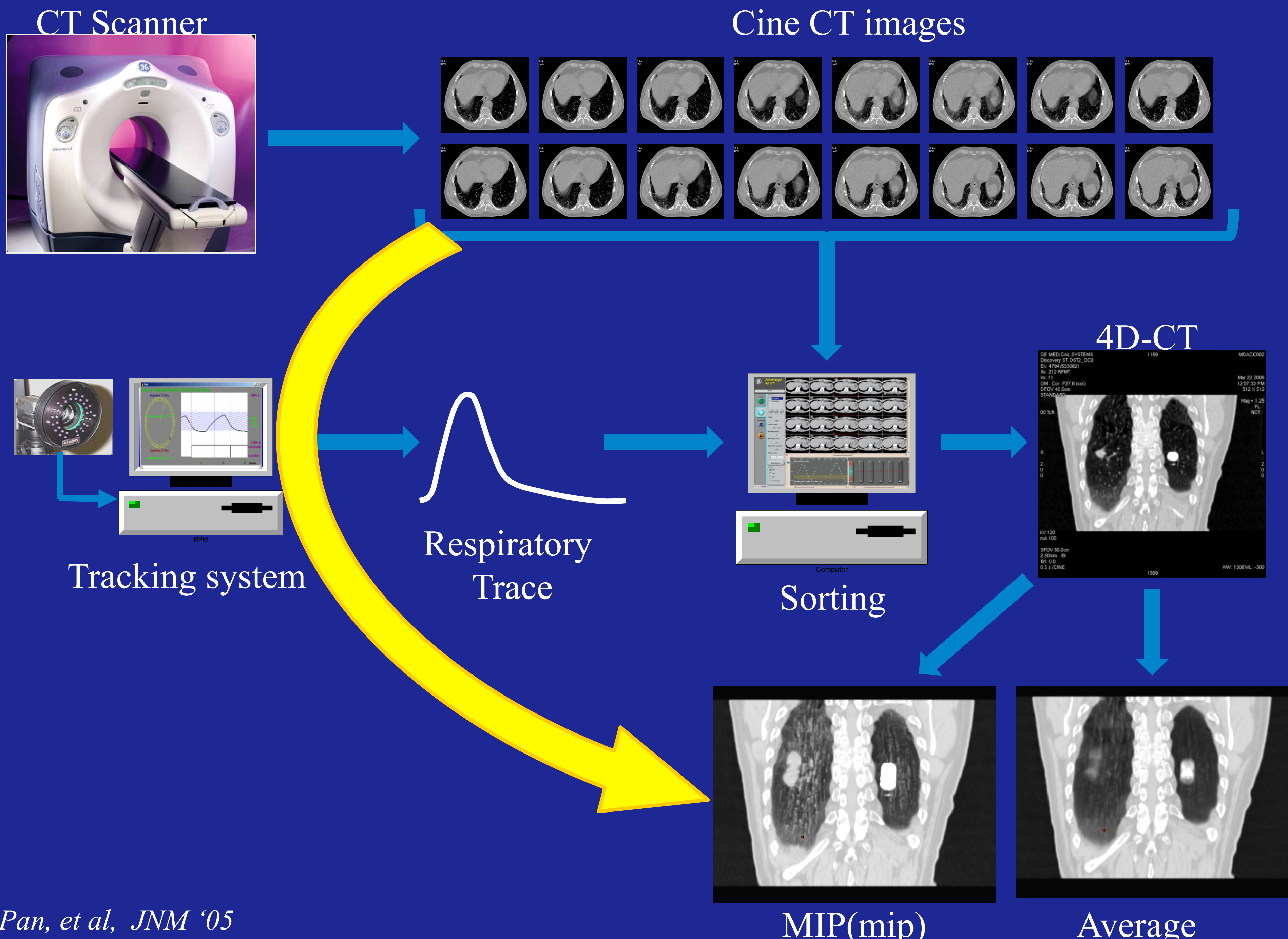


Patient example:



For tumor motion inclusion, it is better that we use all images for MIP. It is called 'original' in GE 4D-CT.

Riegel et al, Med Phys, '09



Pan, et al, JNM ‘05

Average CT (Average intensity projection)

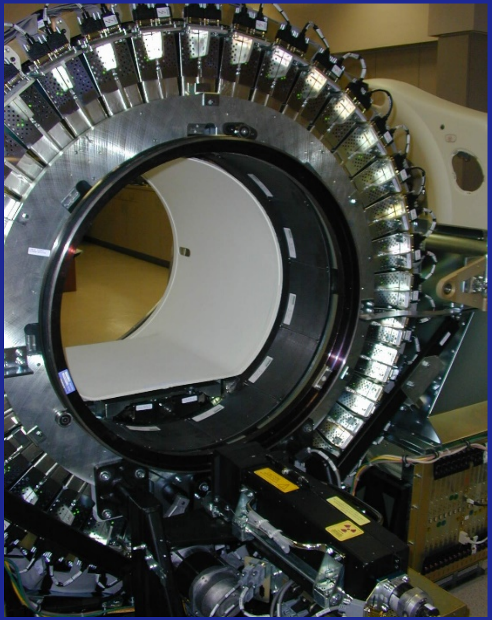
- *Attenuation correction of PET*
- *Dose Calculation*
- *IGRT in RT*

MIP CT

- *ITV or IGTV tumor contouring*

Differences between PET and CT

PET



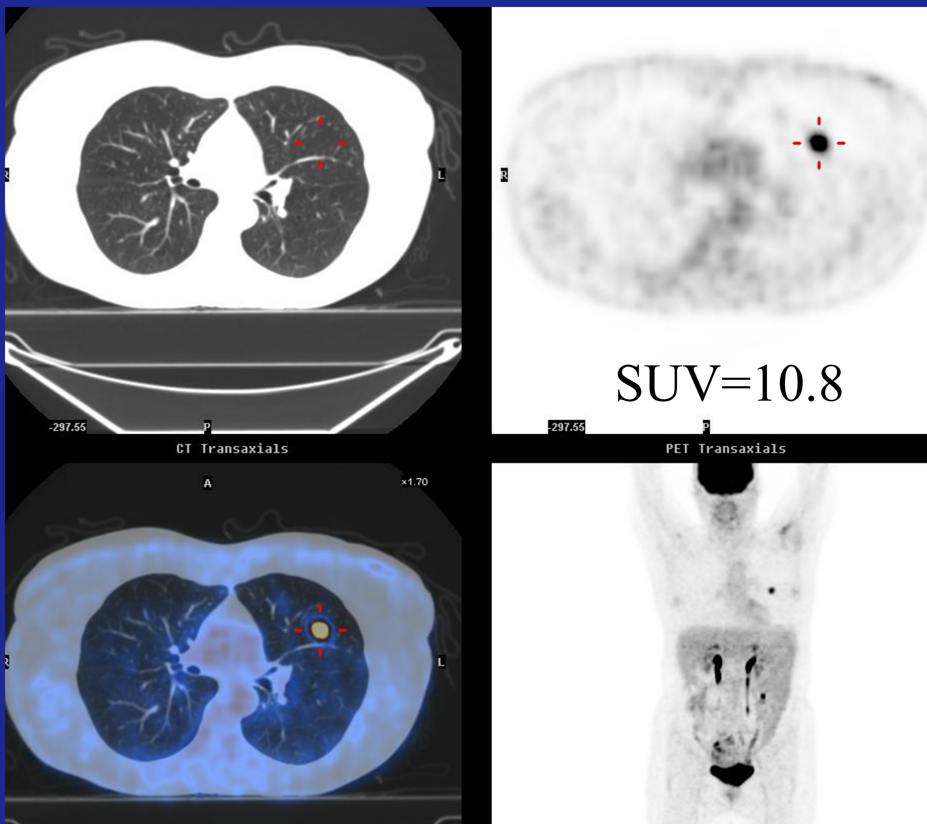
- scan of 15 cm for 3 to 6 mins,
- spatial resolution ~ 6 mm
- temporal resolution ~ breathing cycle

CT – 0.5 sec rotation

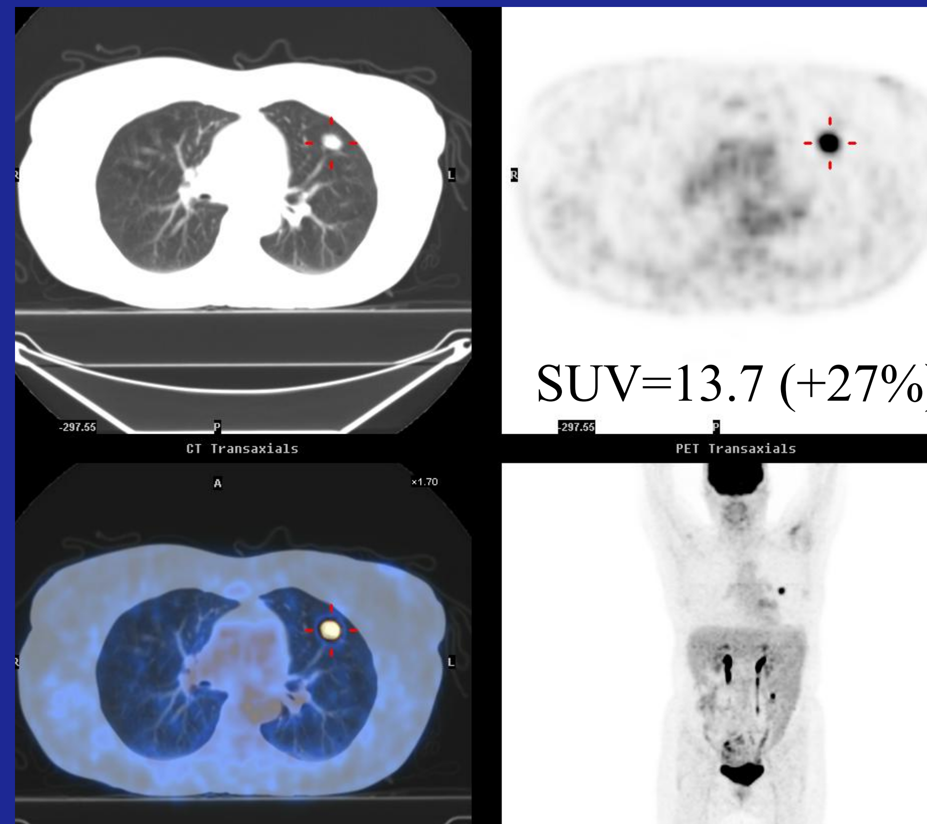
- scan of 90 cm < 20 sec
- spatial resolution < 0.5 mm
- temporal resolution < 1 sec

Potential misalignment between PET and CT images

Patient study #1

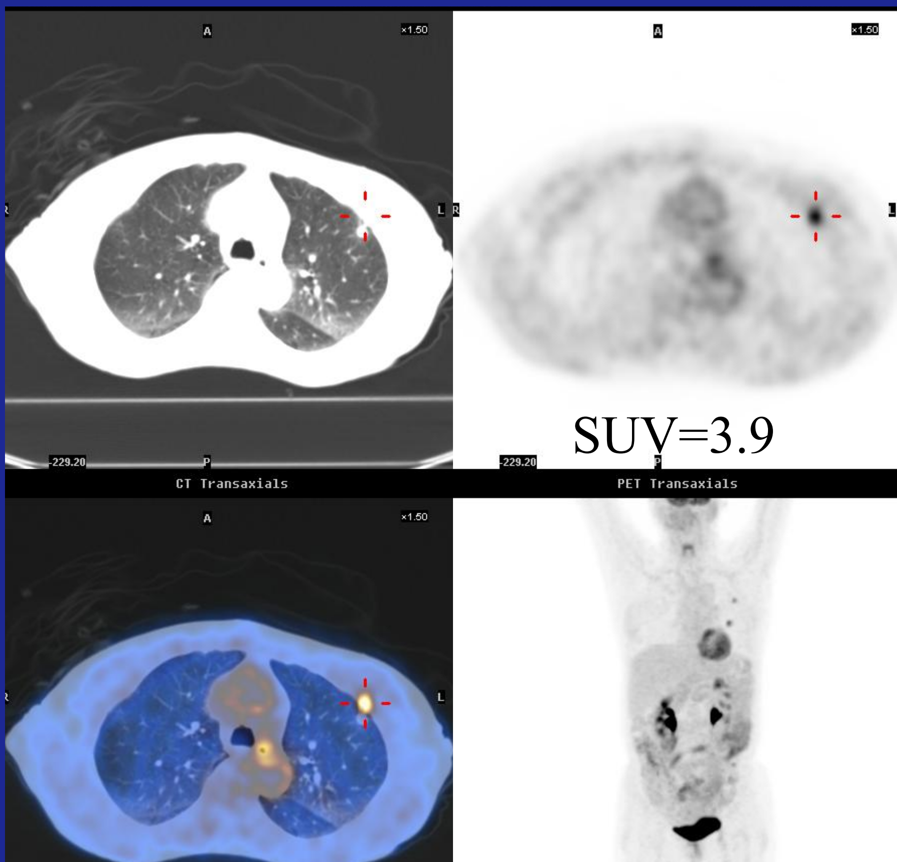


Average PET / FB CT

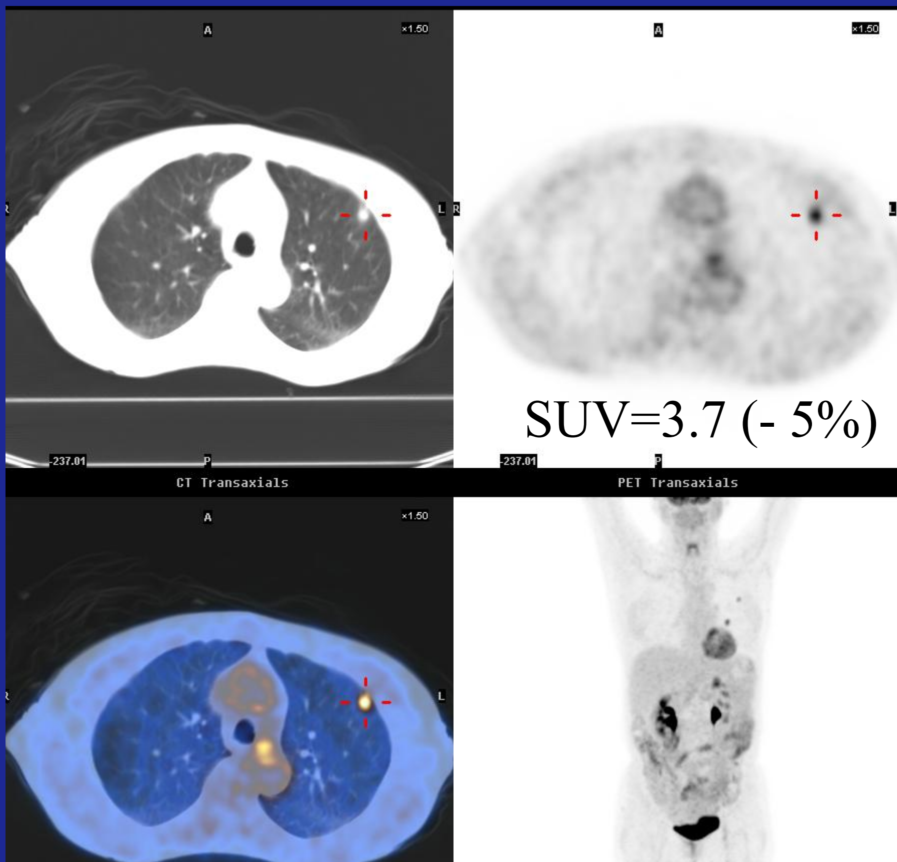


Average PET / average CT

Patient study #2

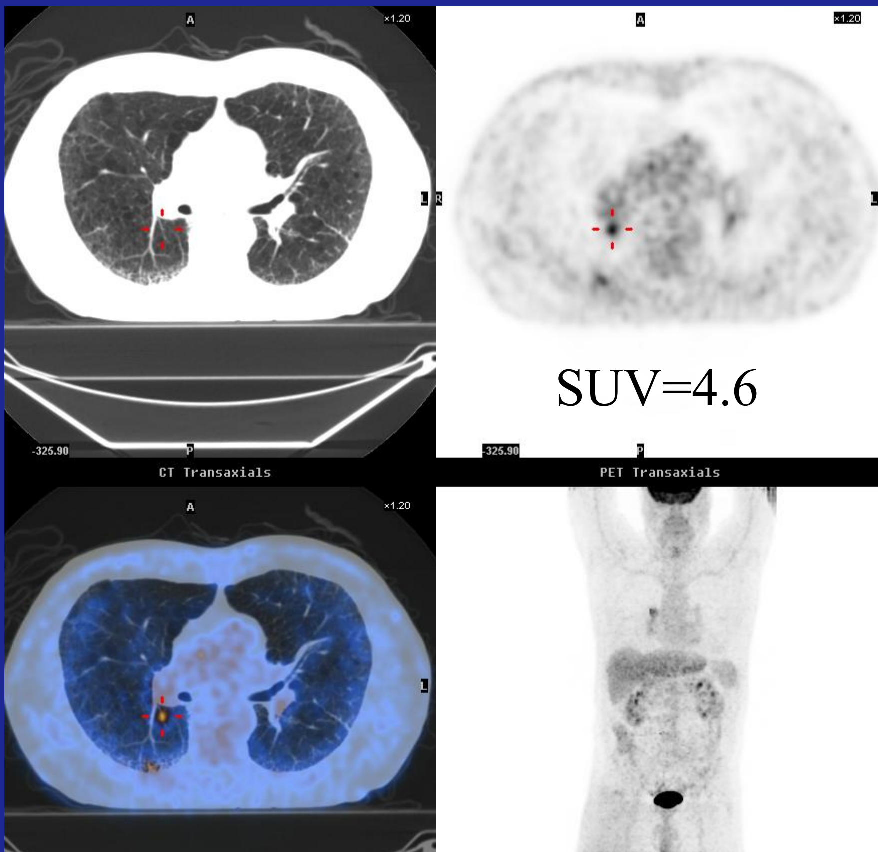


Average PET / FB CT

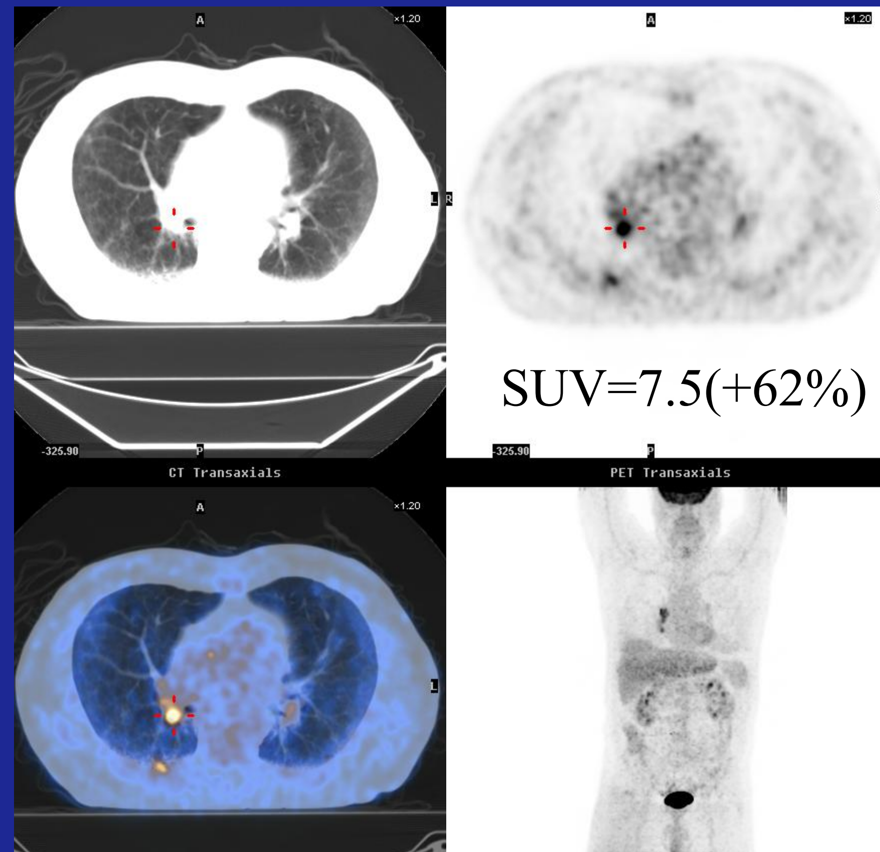


Average PET / average CT

Patient study #3



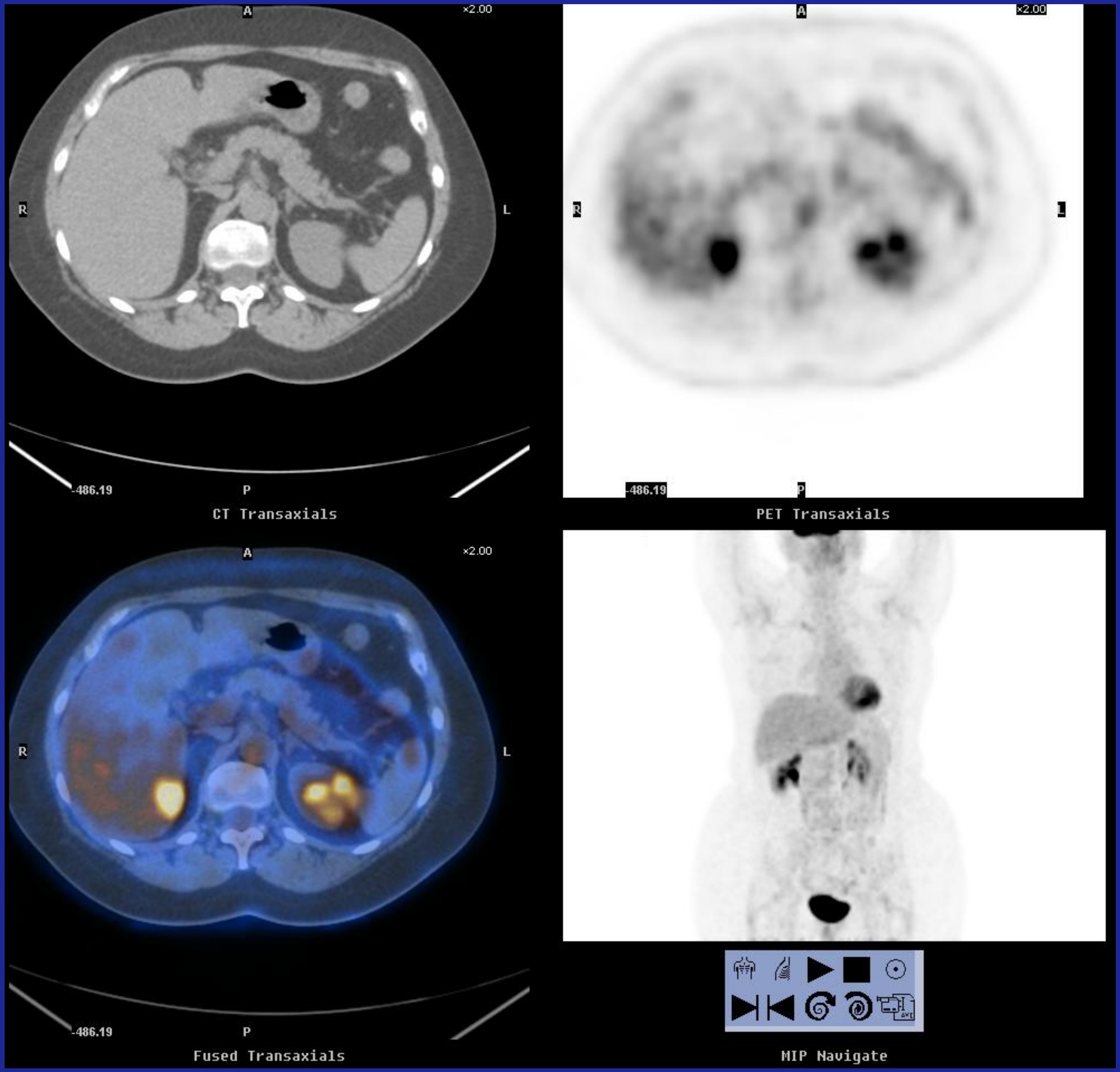
Average PET / FB CT



Average PET / average CT

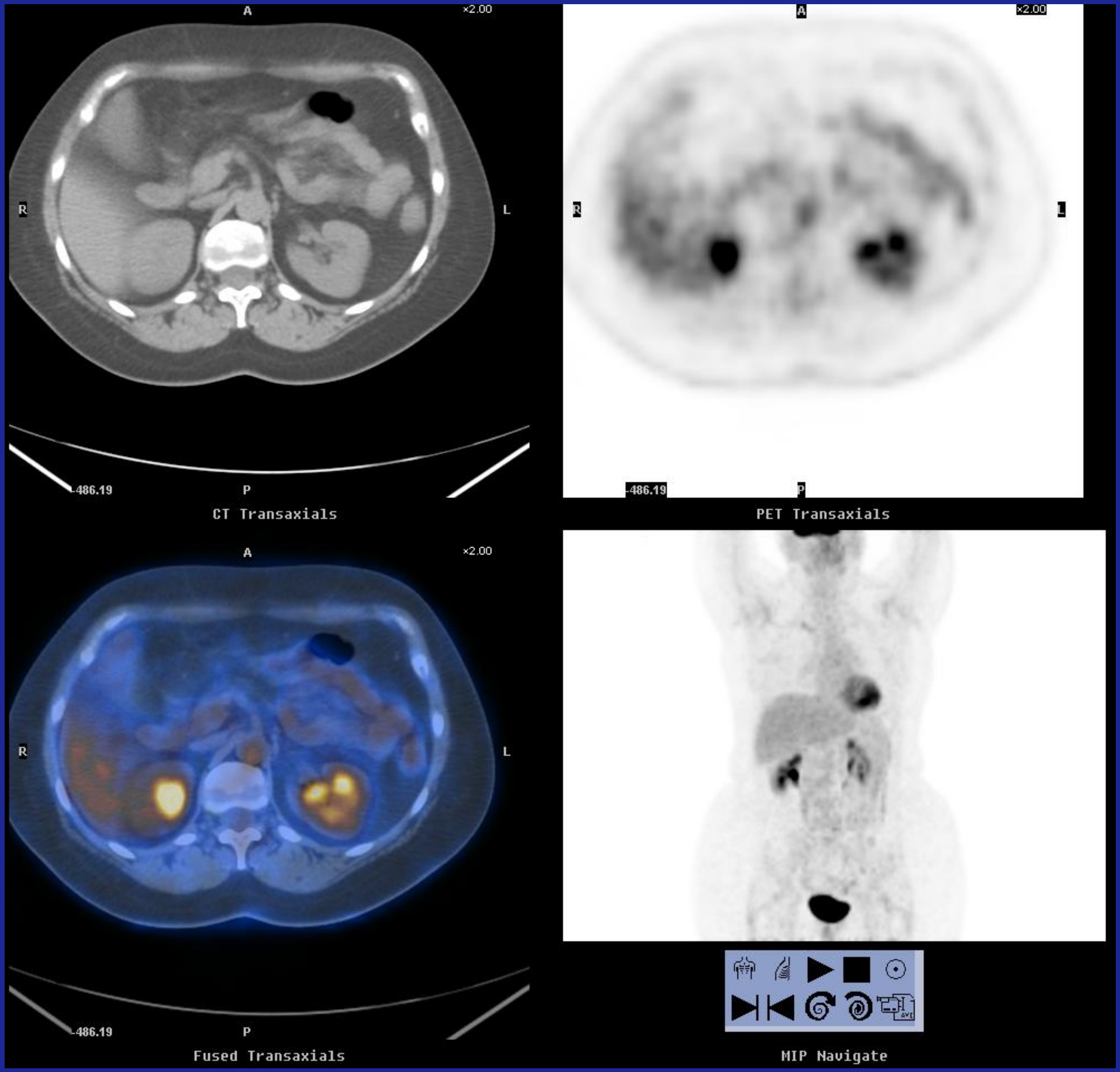
FDG uptake in the liver?

FB CT

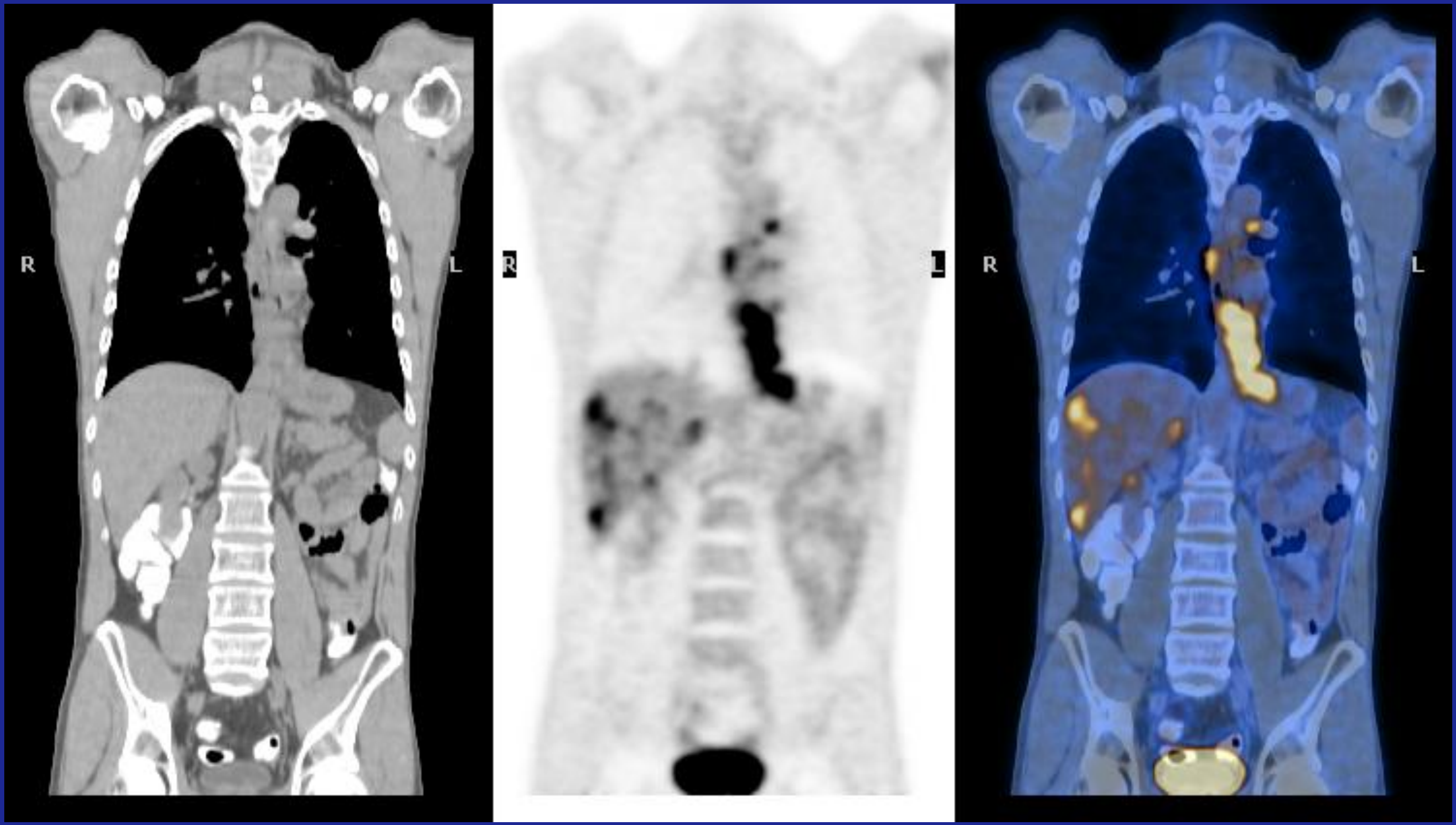


FDG uptake in the kidney

Average CT

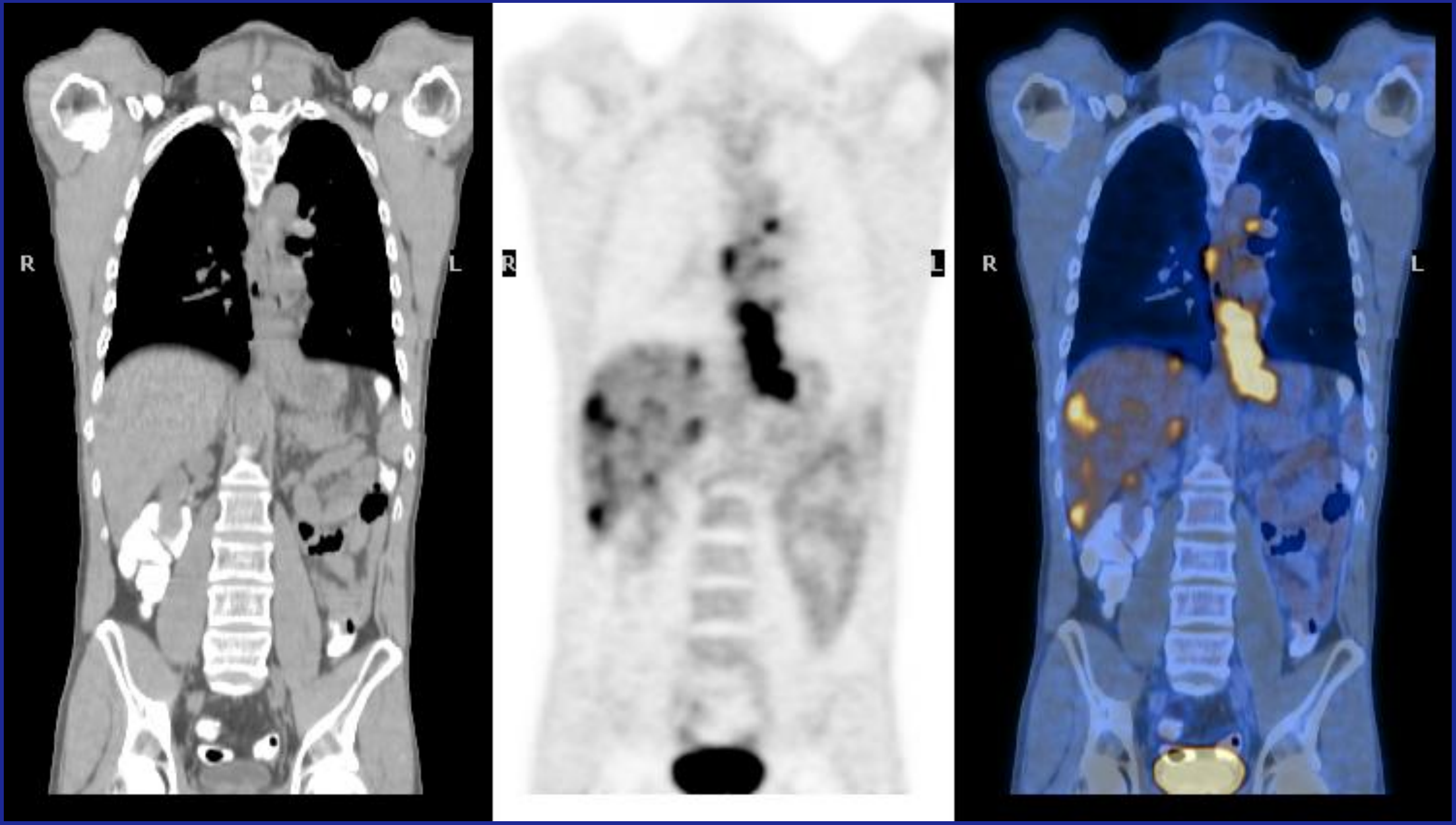


Lung lesion or liver lesion?



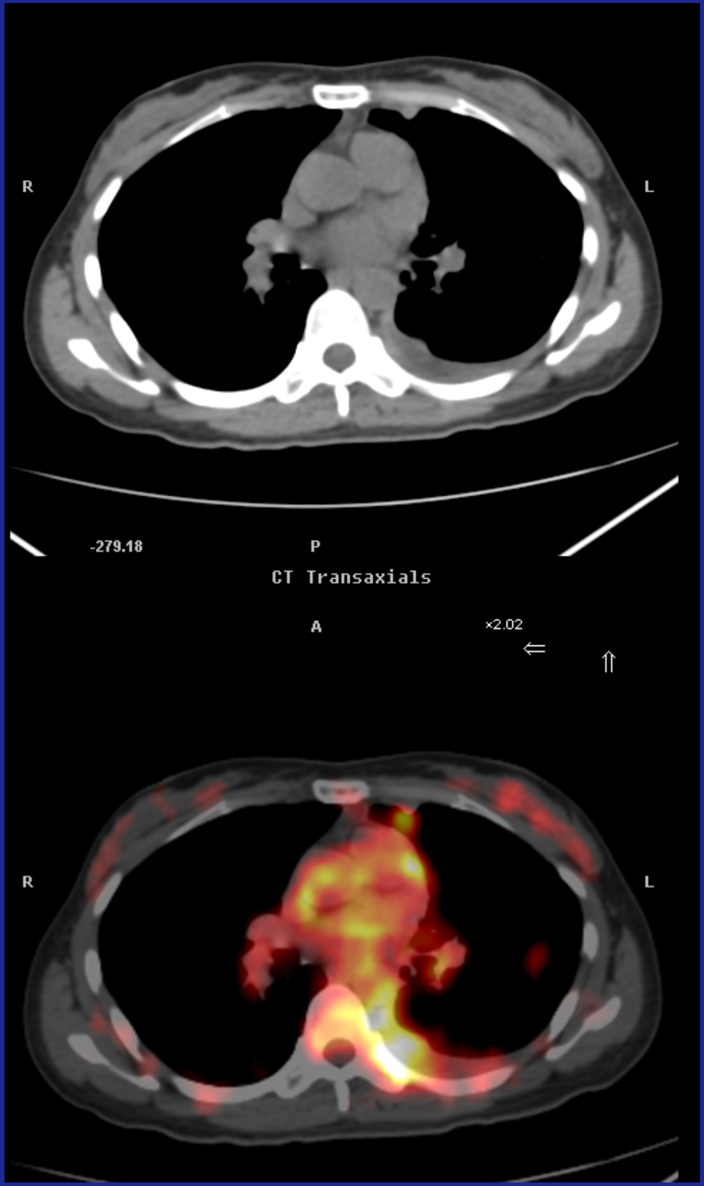
FB CT Average PET Average PET / FB CT

Lung lesion or liver lesion?

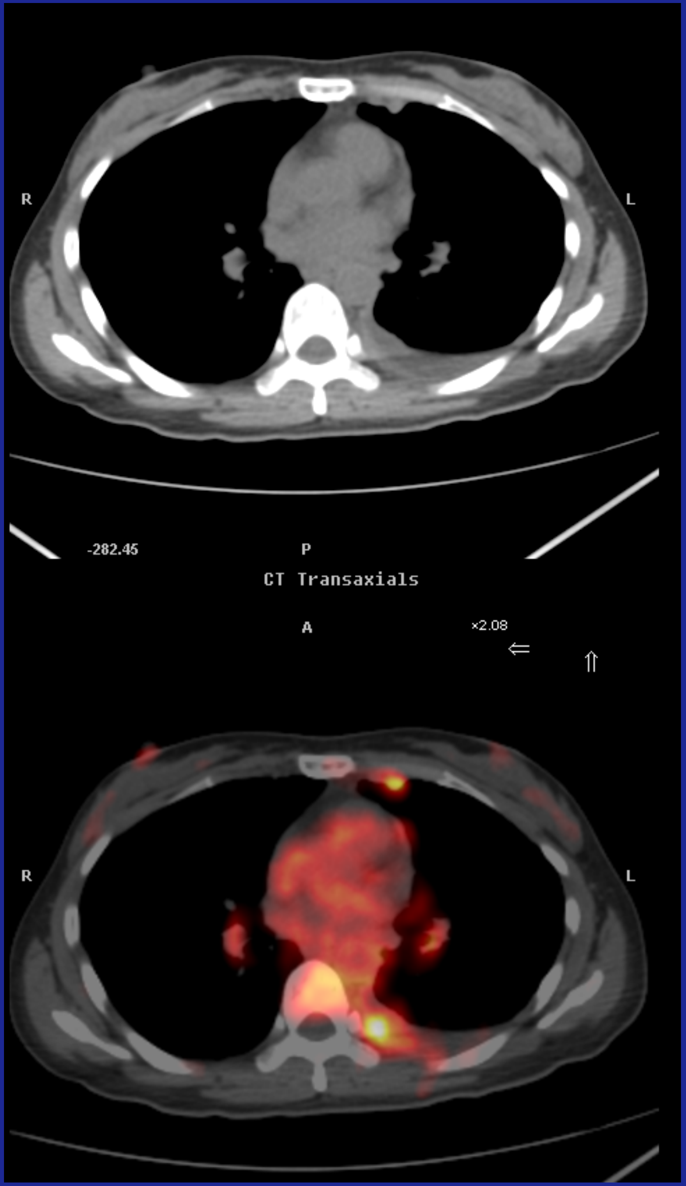


Average CT　　Average PET　　Average PET / average CT

Bone involvement ?

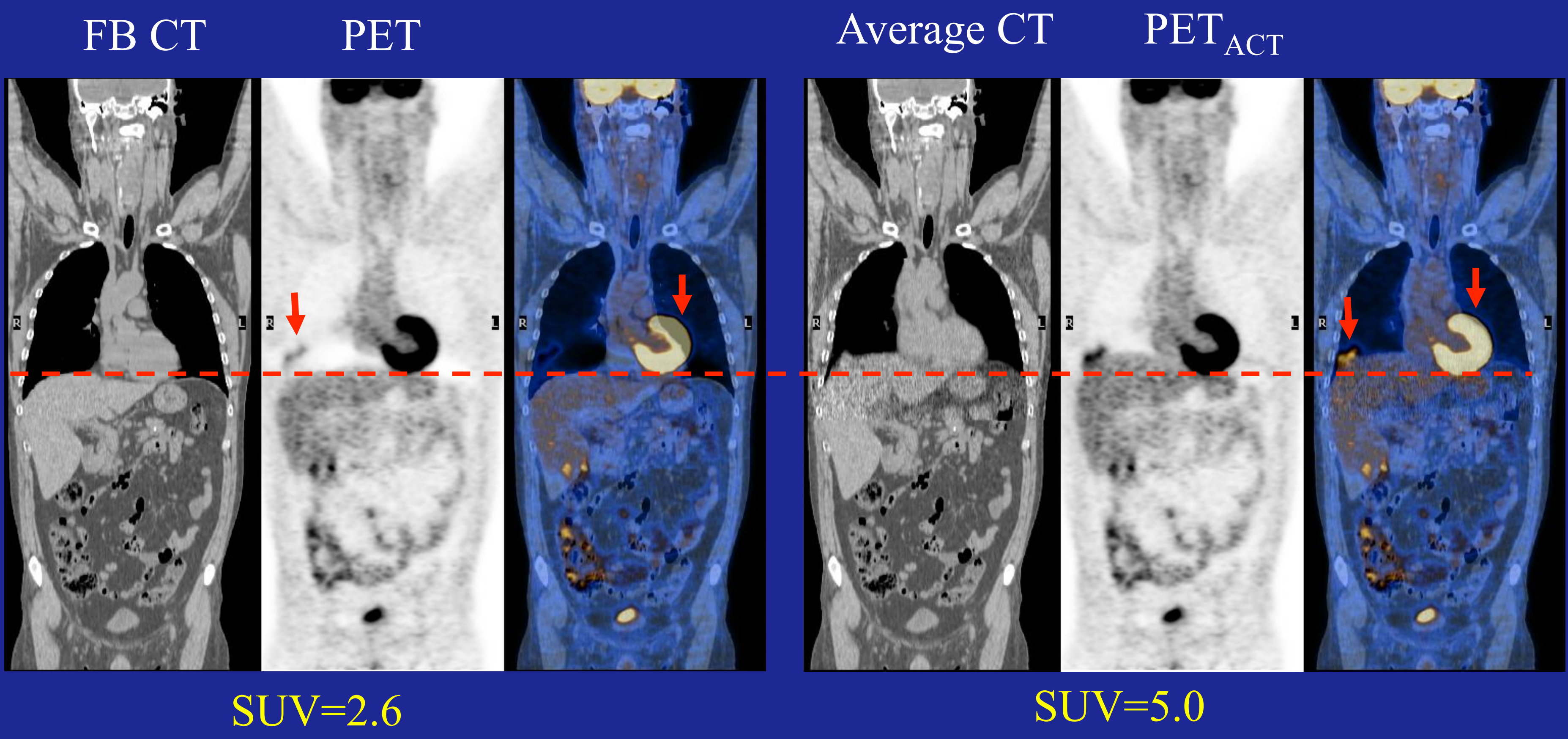


FB CT

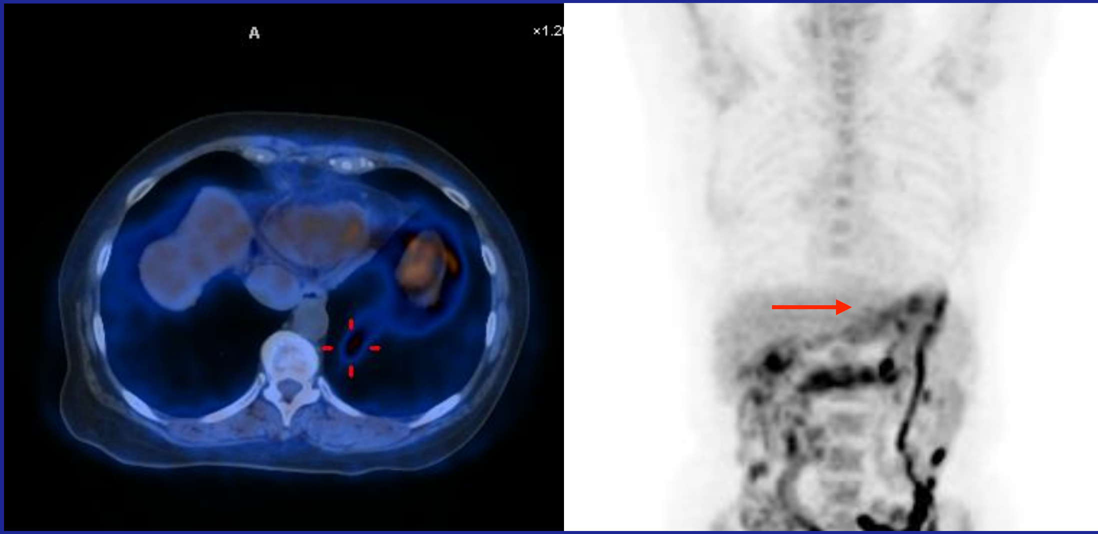


Average CT

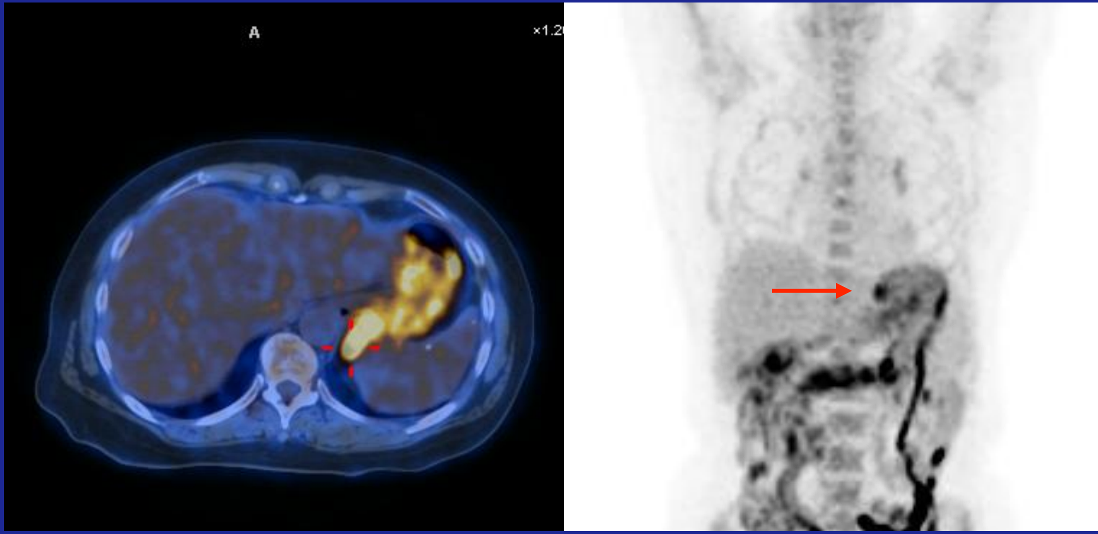
Tumor and cardiac imaging



Improve the restaging after chemo



PET/CT scan indicated a positive response to induction chemo with FB CT.

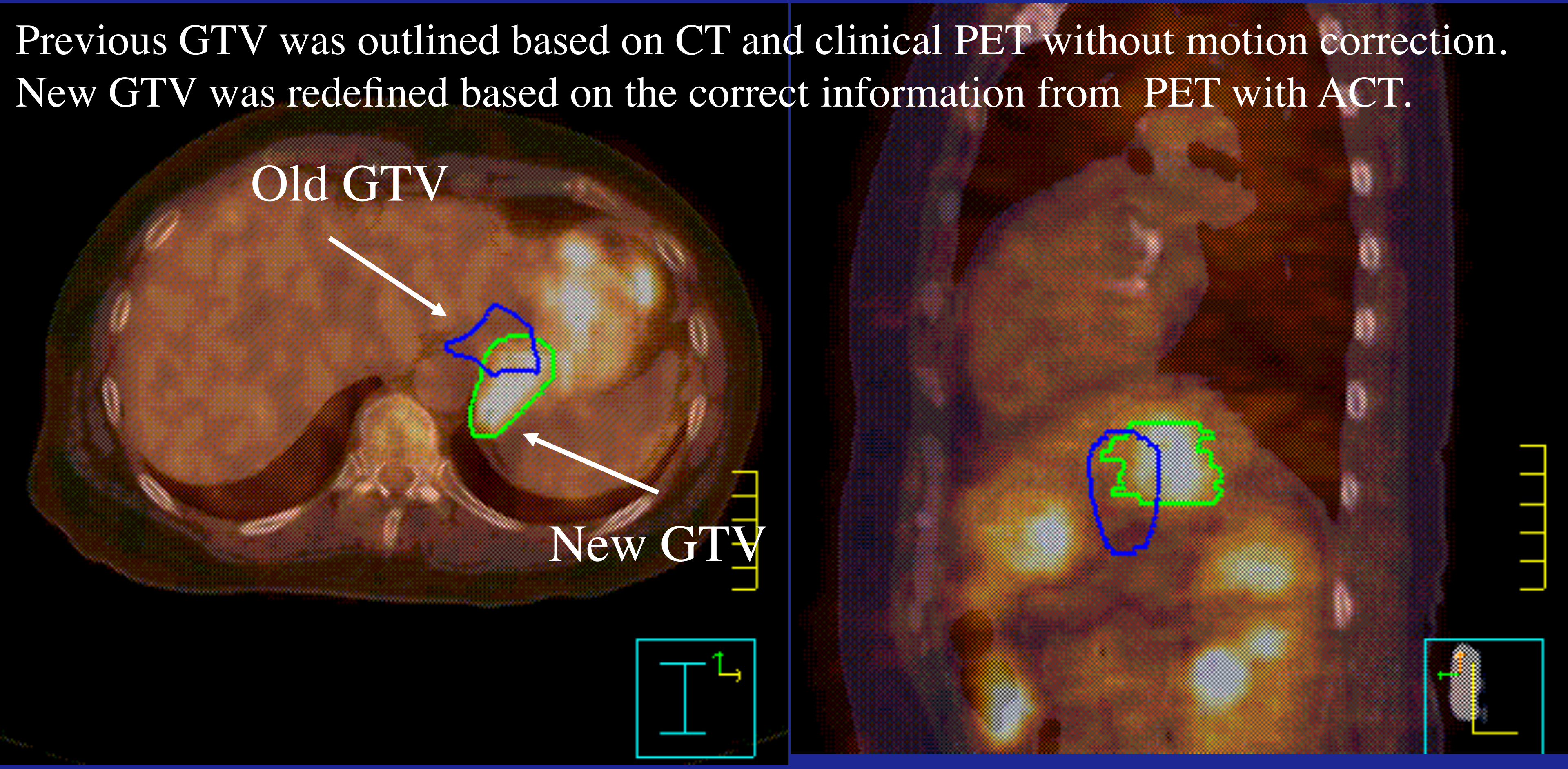


The patient had a negative response to the chemo with average CT.

Pan, et al, Med Phys, '08

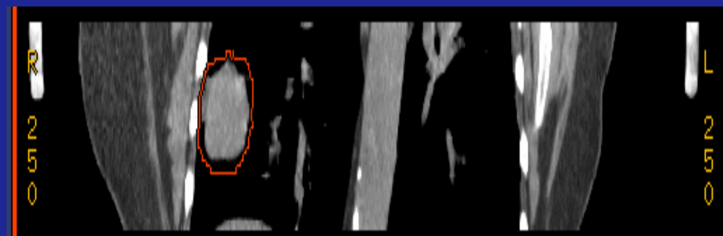
Impact on treatment planning

Previous GTV was outlined based on CT and clinical PET without motion correction. New GTV was redefined based on the correct information from PET with ACT.

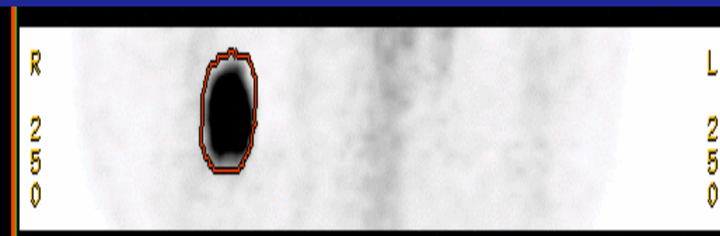


Pan, et al, Med Phys, '08

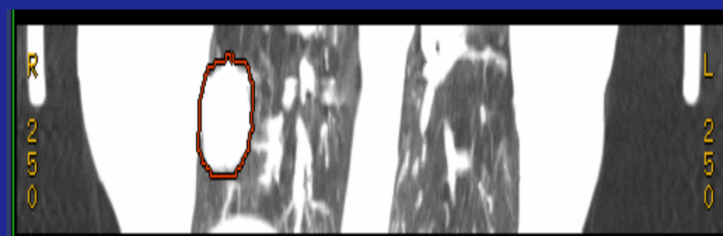
Tumor contouring with MIP CT



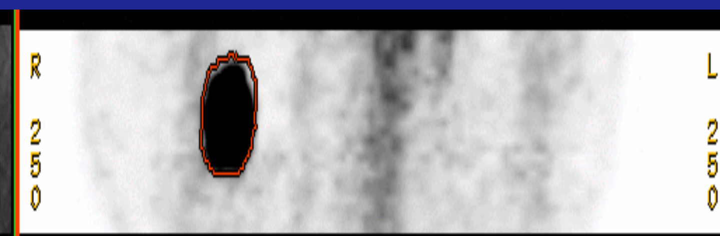
Soft tissue (400,40)



40% SUV_{max}

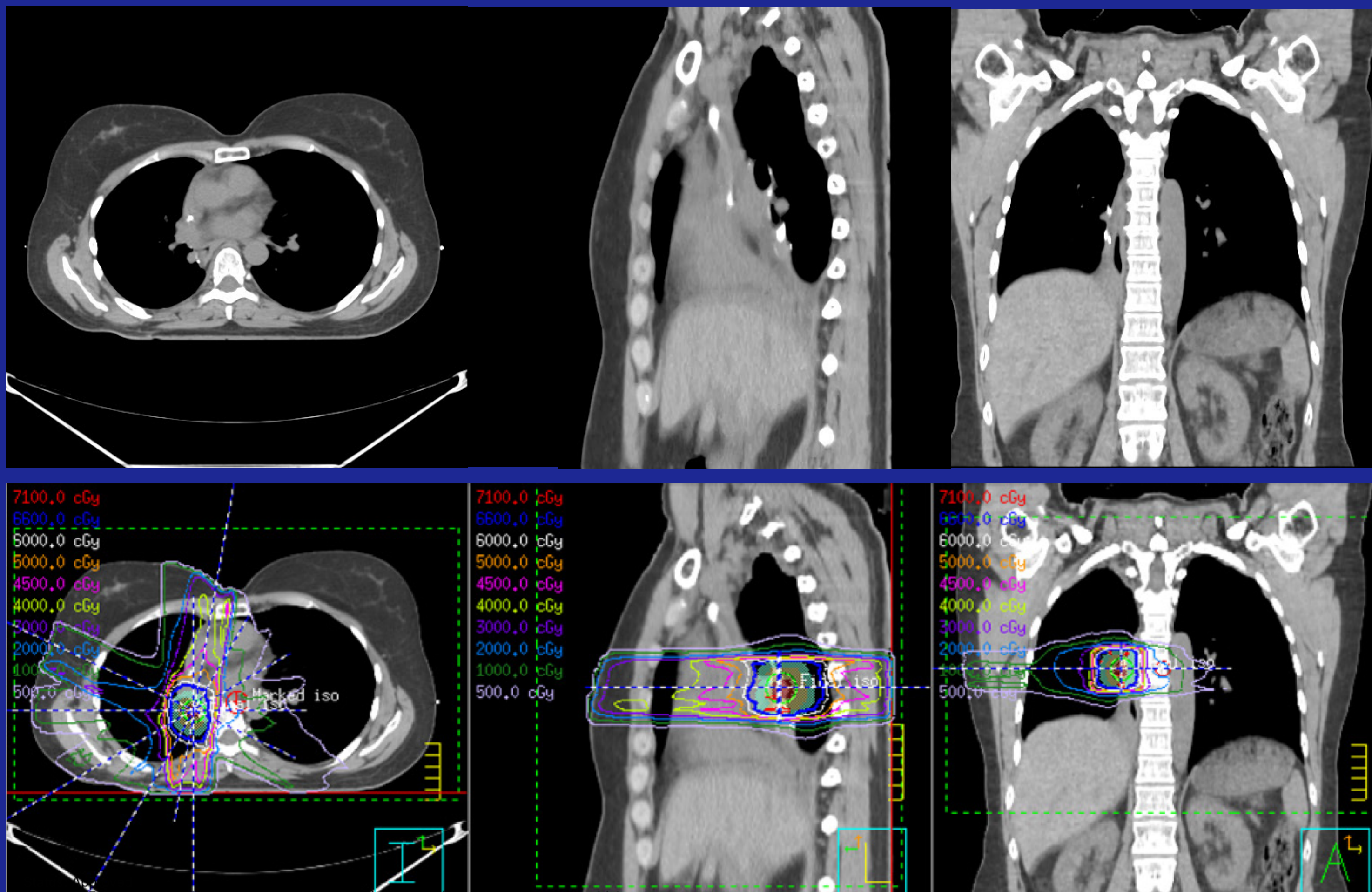


Lung (1000,-700)

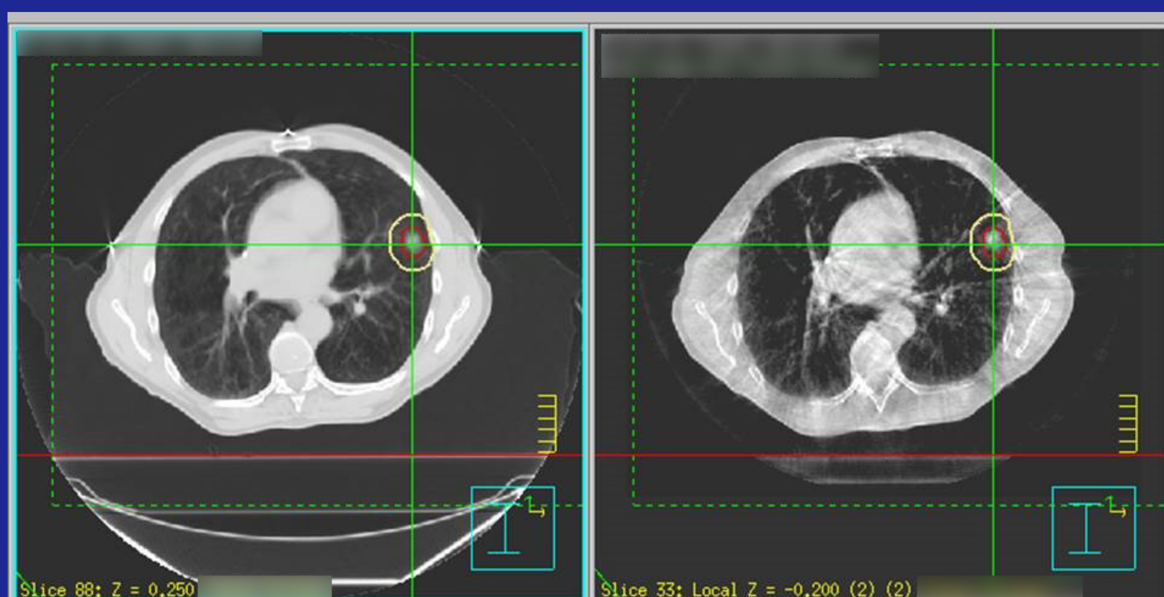


20% SUV_{max}

Average CT for RT dose calculation



Average CT for IGRT

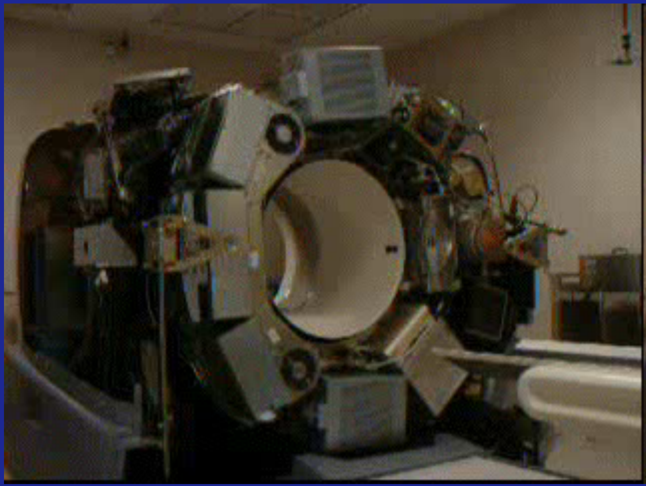


Average CT (ACT)

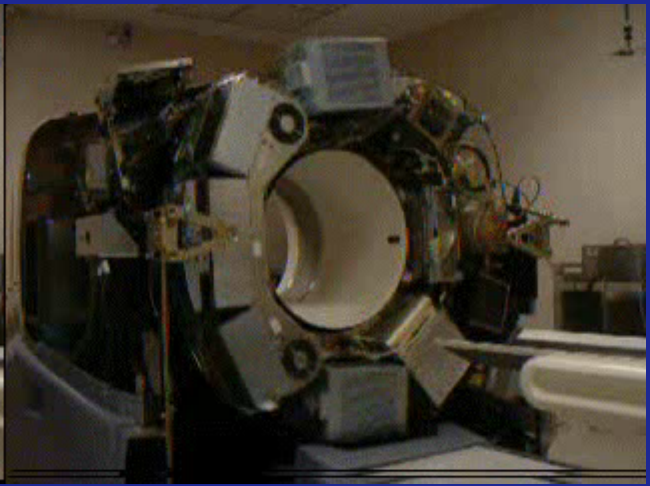
Slow CT $\neq$ *Average CT*

Long slow scan $\neq$ *Long fast scan*

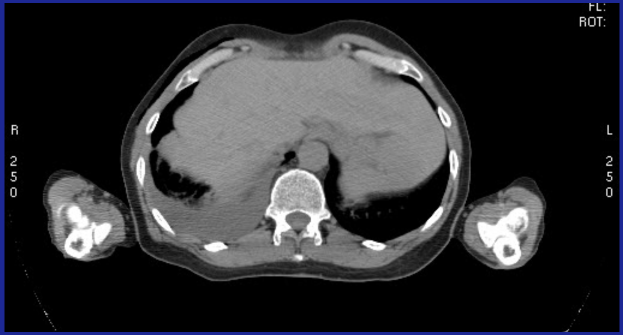
Slow scan CT artifacts



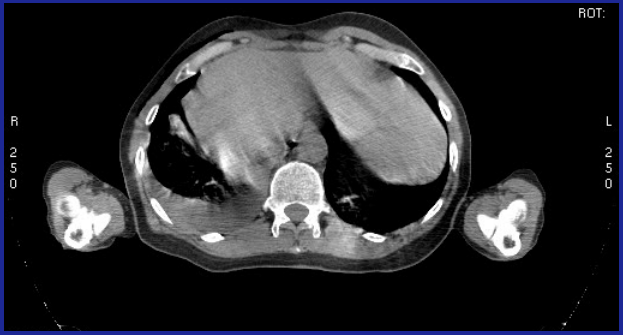
0.5 sec rotation



4 sec rotation



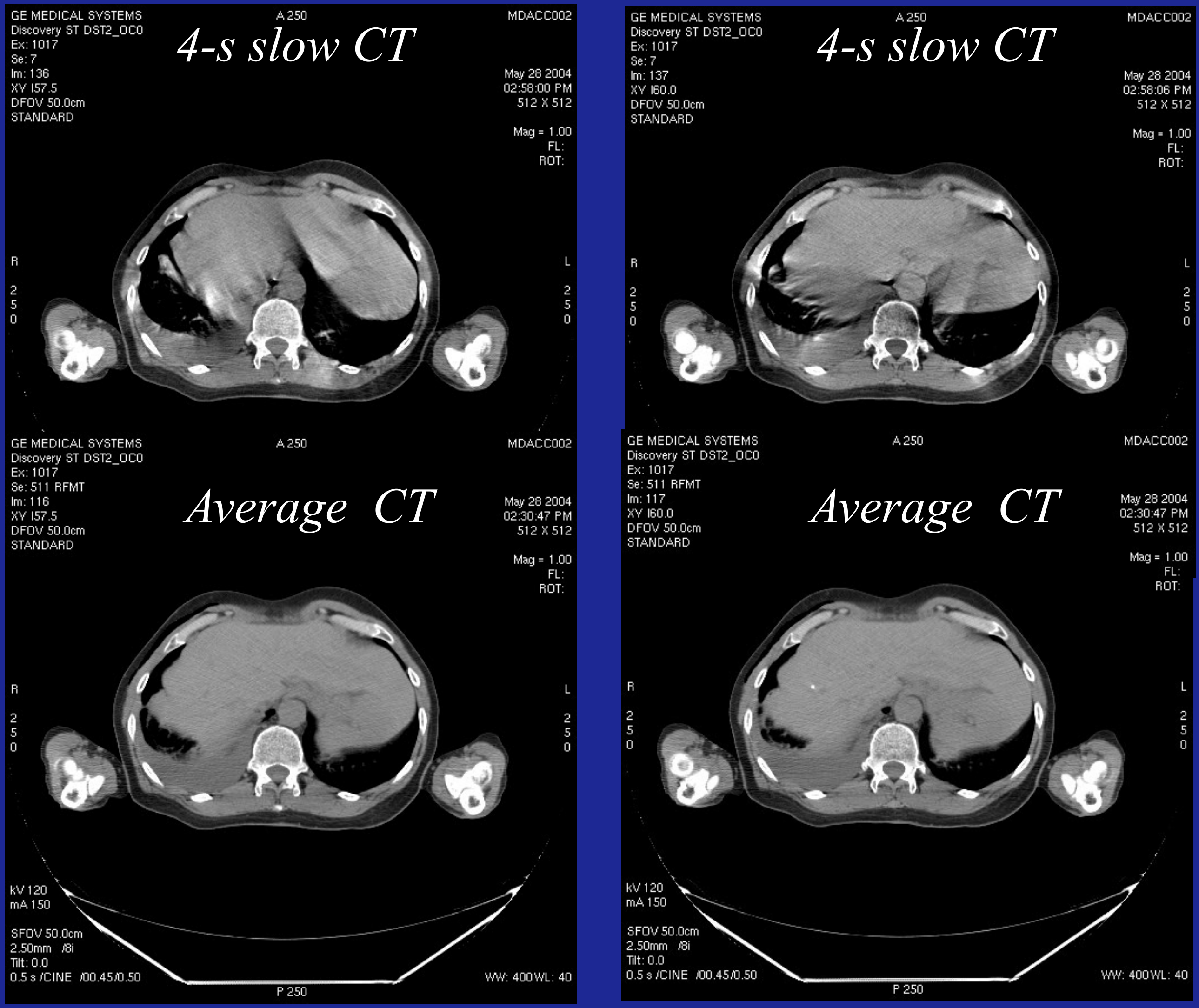
Average CT (4 sec)



Slow CT (4 sec)

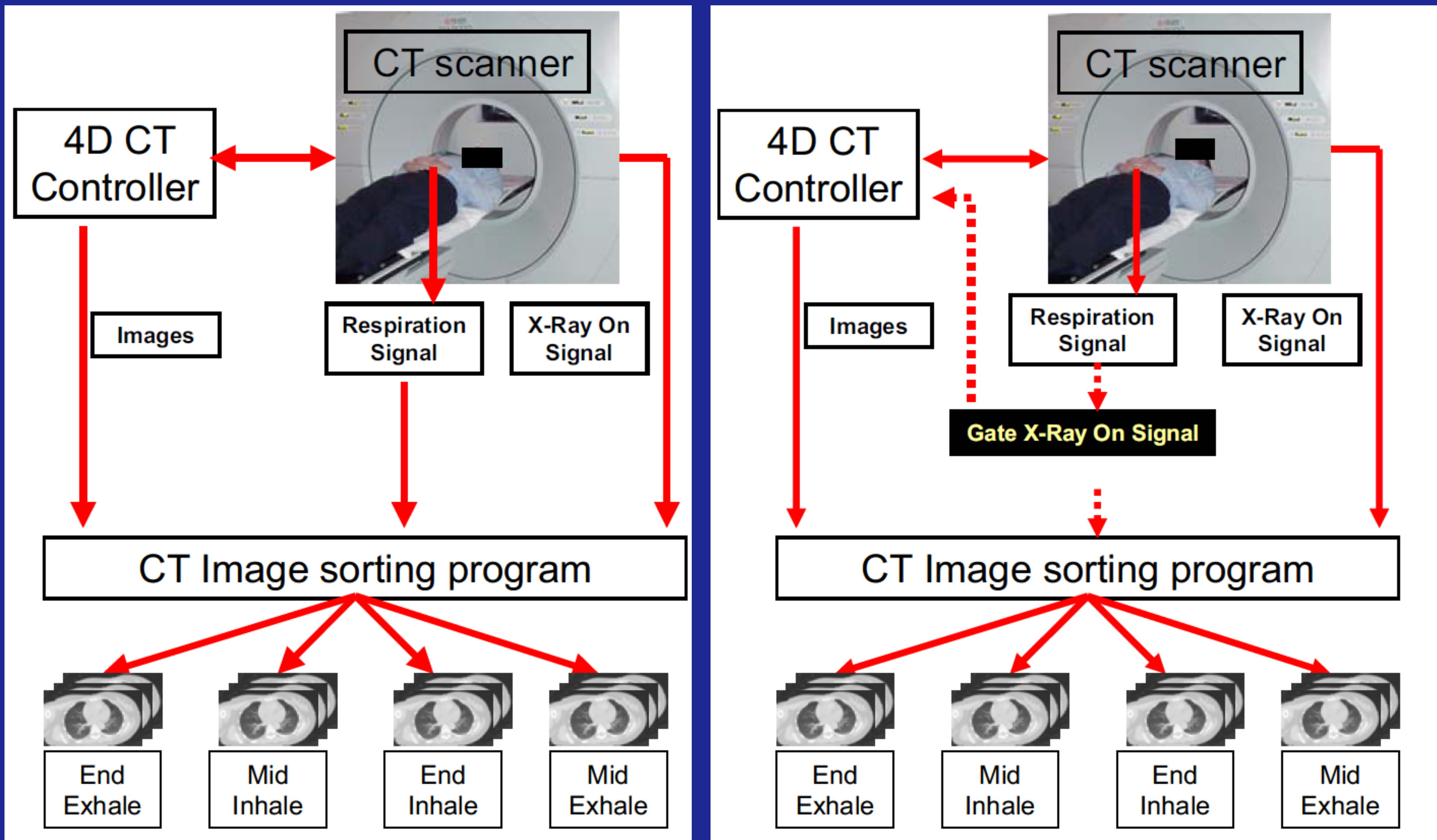
Average CT is better than slow CT

(2 adjacent CT slices of 2.5 mm apart)



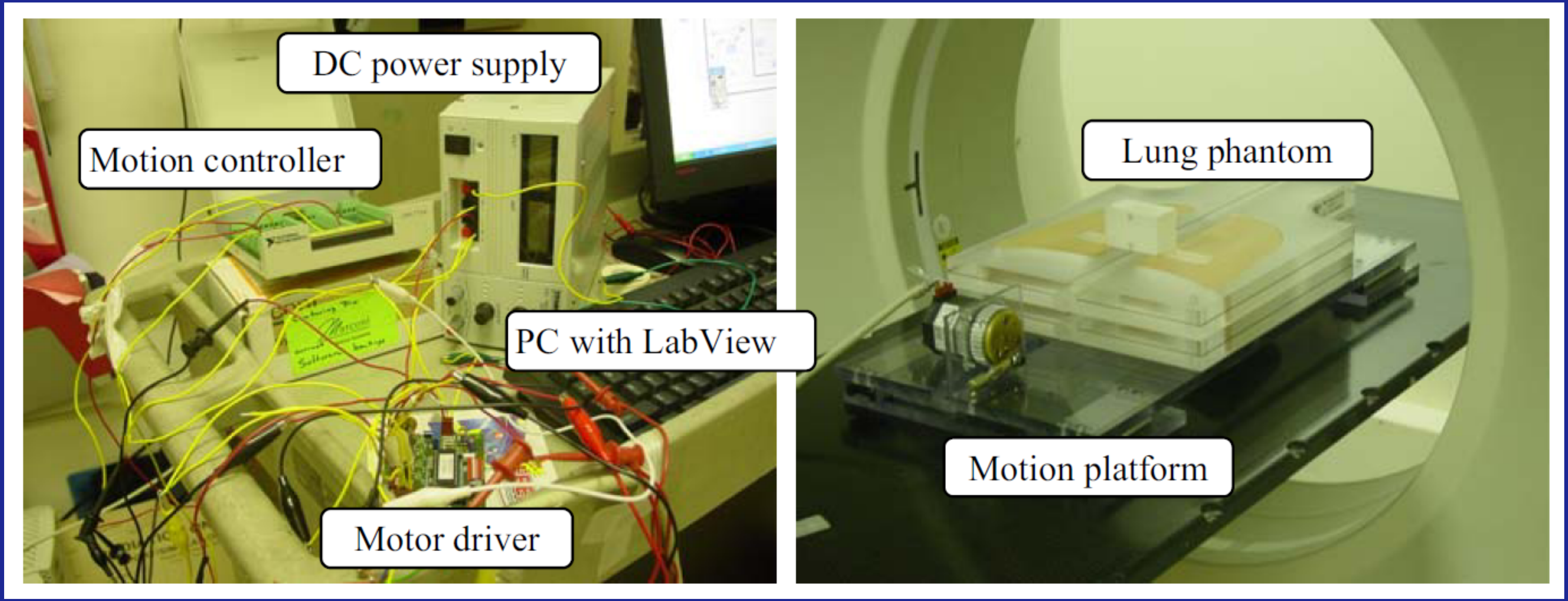
Prospective 4D-CT on SSCT

Prospective 4D-CT



Keall et al, Australas Phys. Eng. Sci. Med. 2007

Prospective 4D-CT feasibility



Implemented on Philips PQ5000, but no patient scan was conducted.

Keall et al, Australas Phys. Eng. Sci. Med. 2007

Prospective cine 4D-CT (applicable today)

IOP Publishing | Institute of Physics and Engineering in Medicine Physics in Medicine & Biology
Phys. Med. Biol. **62** (2017) N350–N361 https://doi.org/10.1088/1361-6560/aa7a9b

Note

New prospective 4D-CT for mitigating the effects of irregular respiratory motion

Tinsu Pan, Rachael M Martin and Dershan Luo

Department of Imaging Physics, The University of Texas, M D Anderson Cancer Center, 1515 Holcombe Blvd., Unit 1352, Houston, TX 77030-4009, United States of America

E-mail: tpan@mdanderson.org

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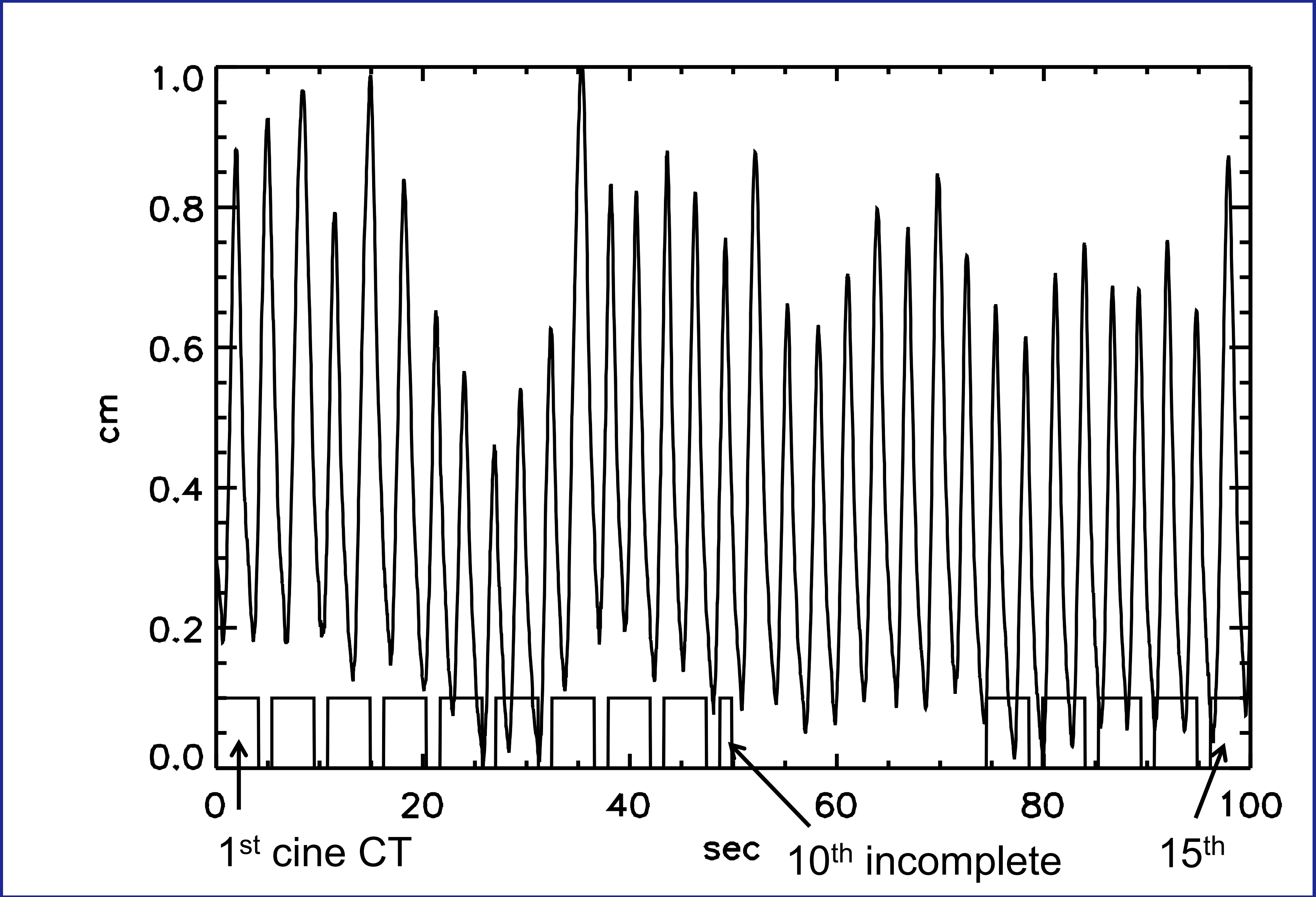
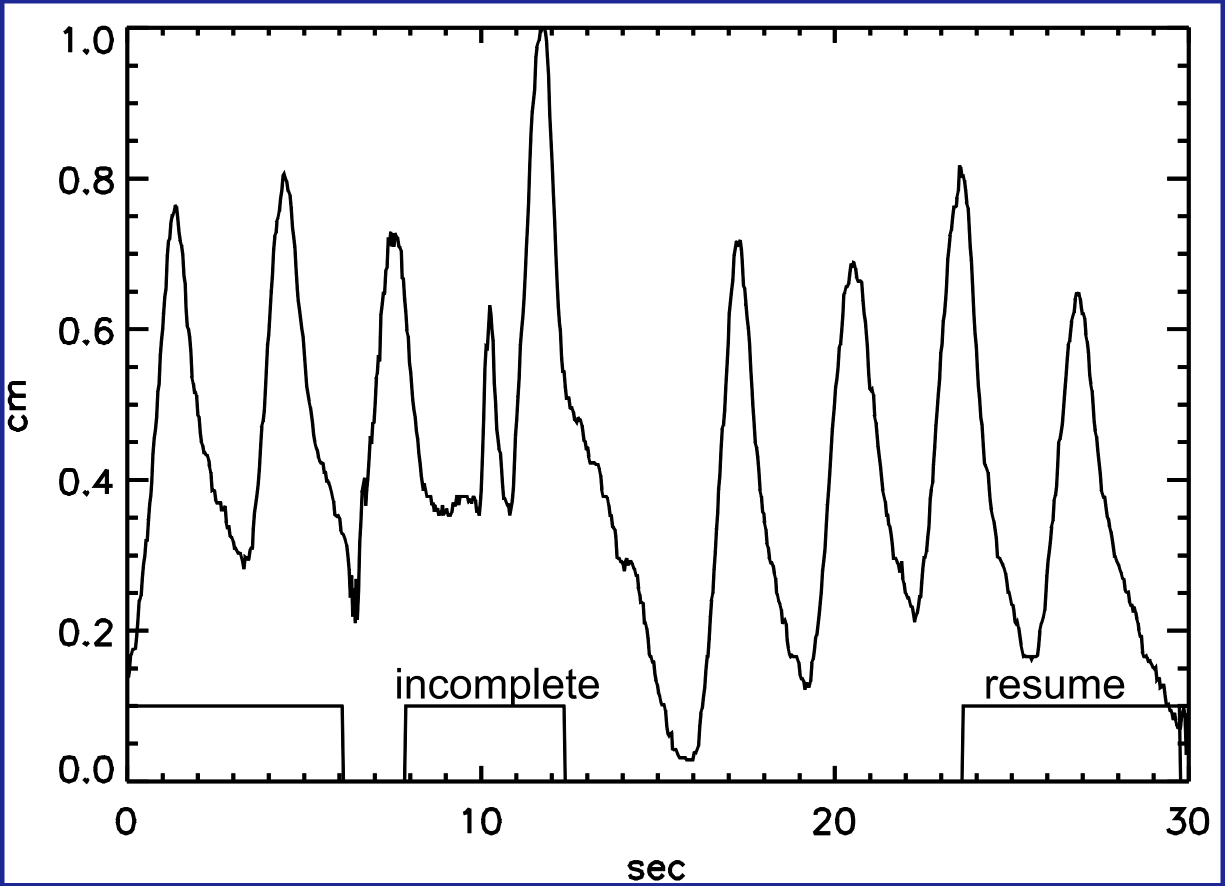
CrossMark

Motivation

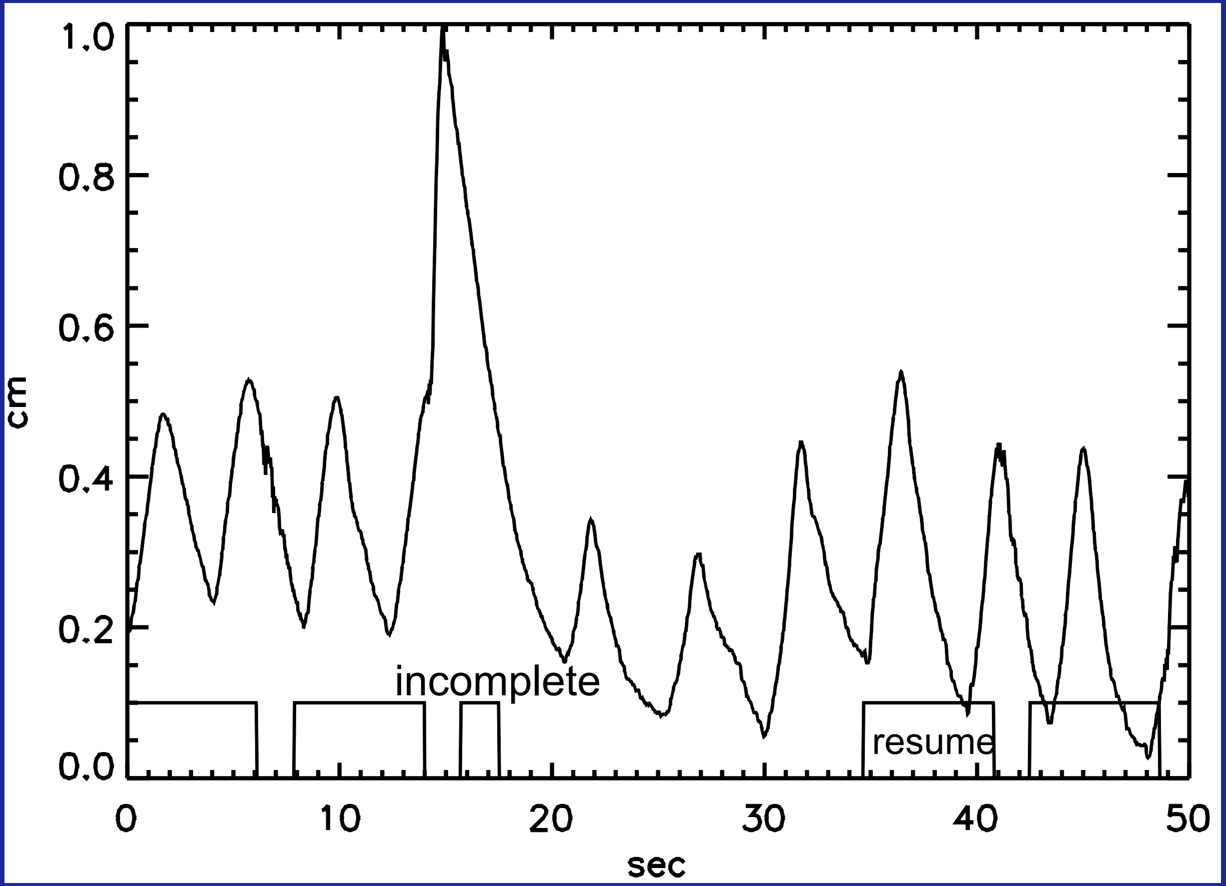


1.0
0.8
0.6
0.4
0.2
0.0
cm
0
20
40
60
80
100
sec
1st cine CT
10th incomplete
15th

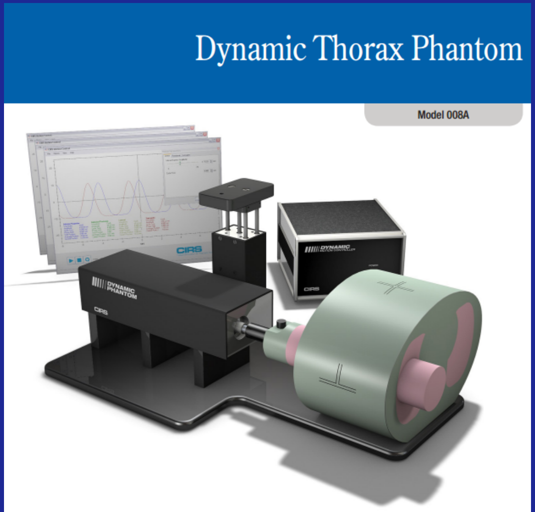
Identification of irregular respiration 1

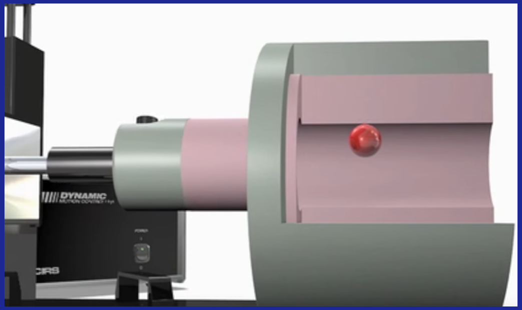


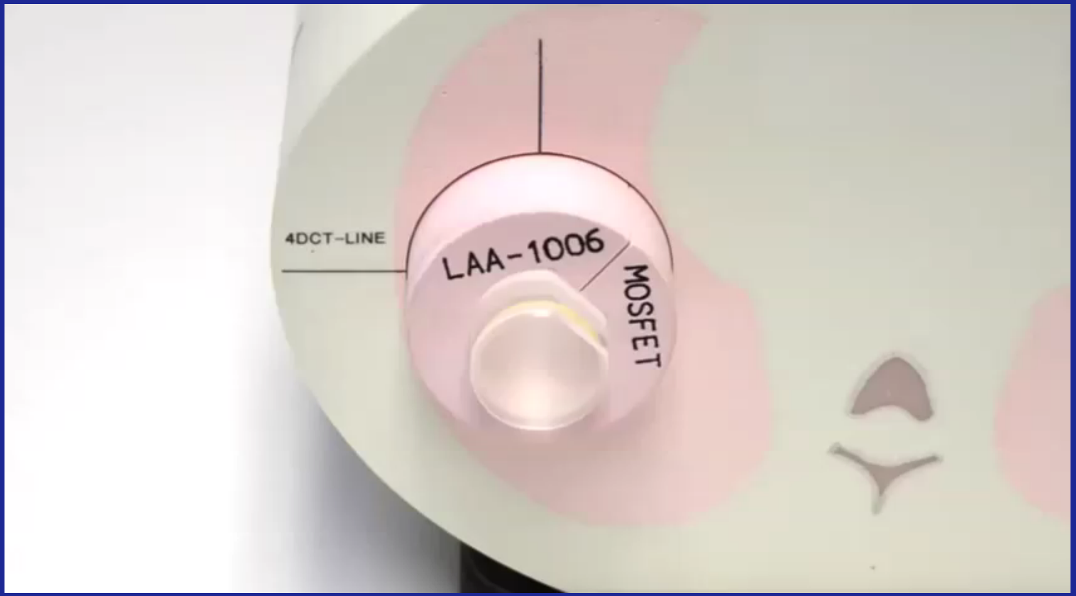
Identification of irregular respiration 2



CIRS Dynamic Thorax Phantom

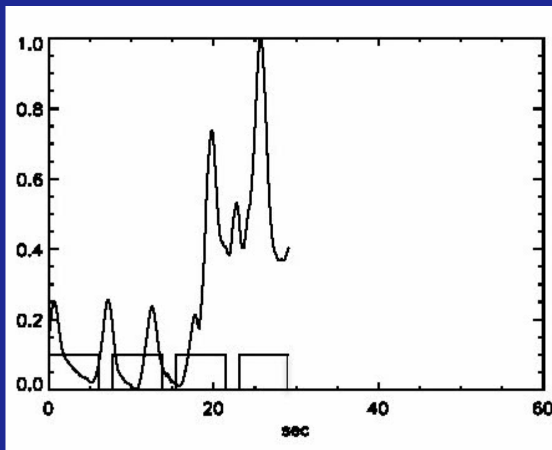


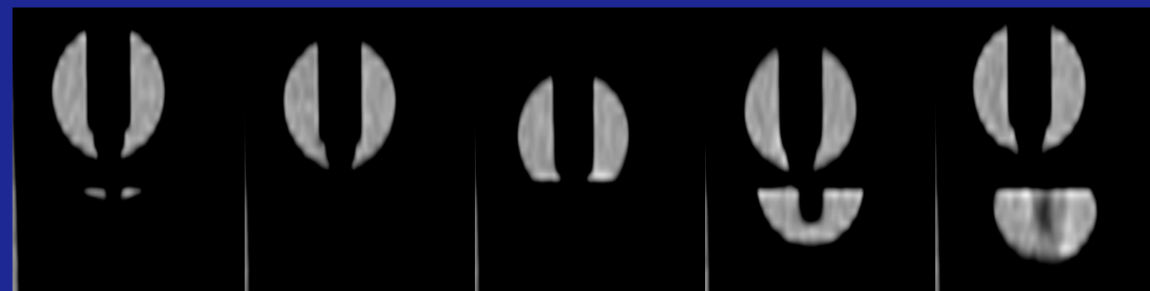




Phantom Experiment

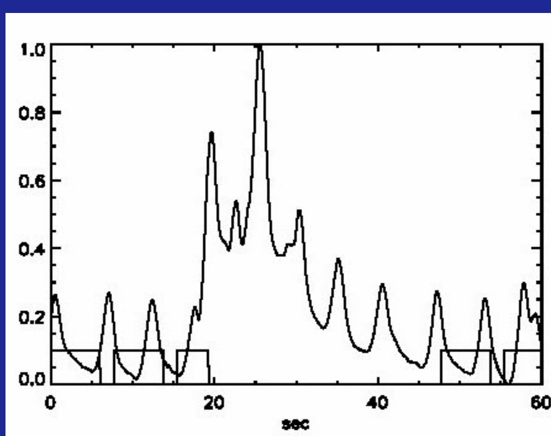
Irregular respiration in conventional 4D-CT

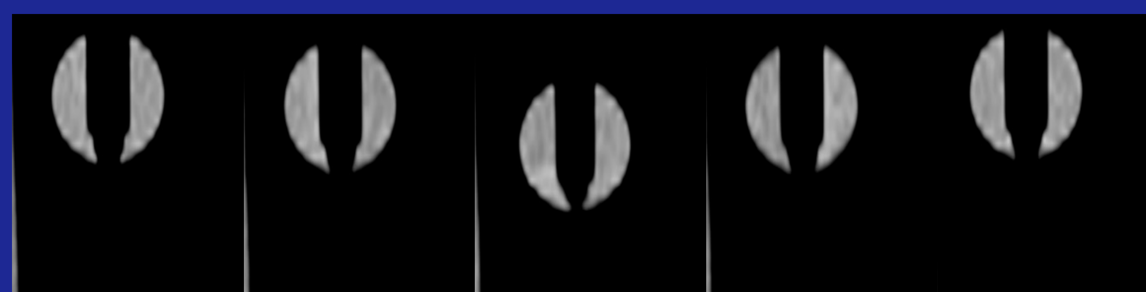




0% 20% 40% 60% 80%

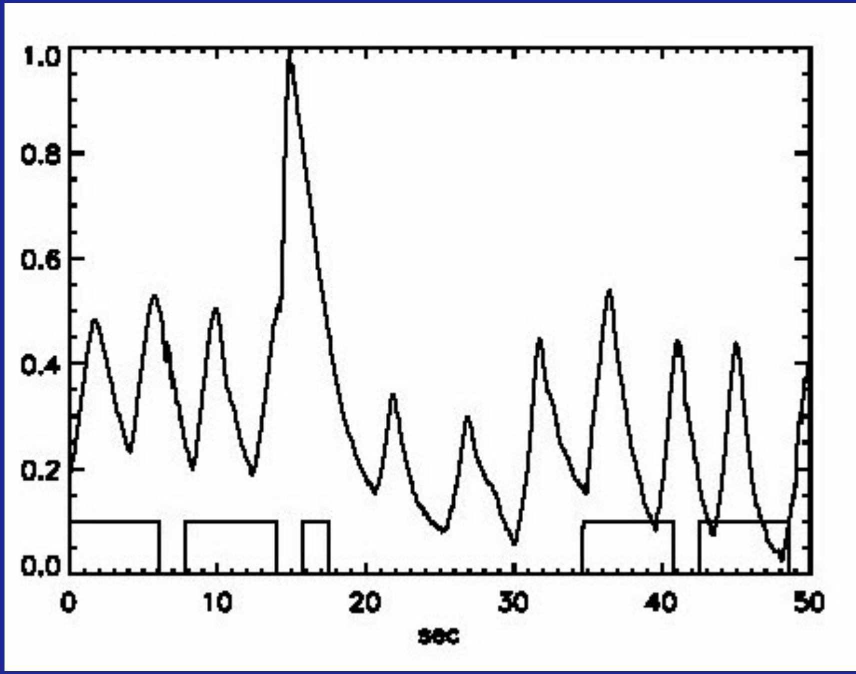
Skip irregular respiration in Prospective 4D-CT



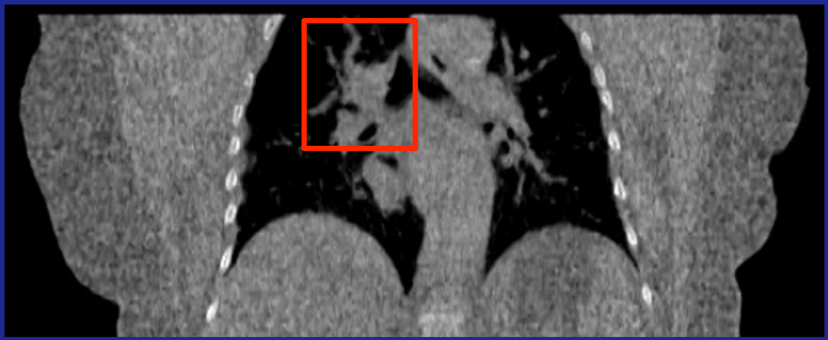


0% 20% 40% 60% 80%

Prospective 4D-CT (1)



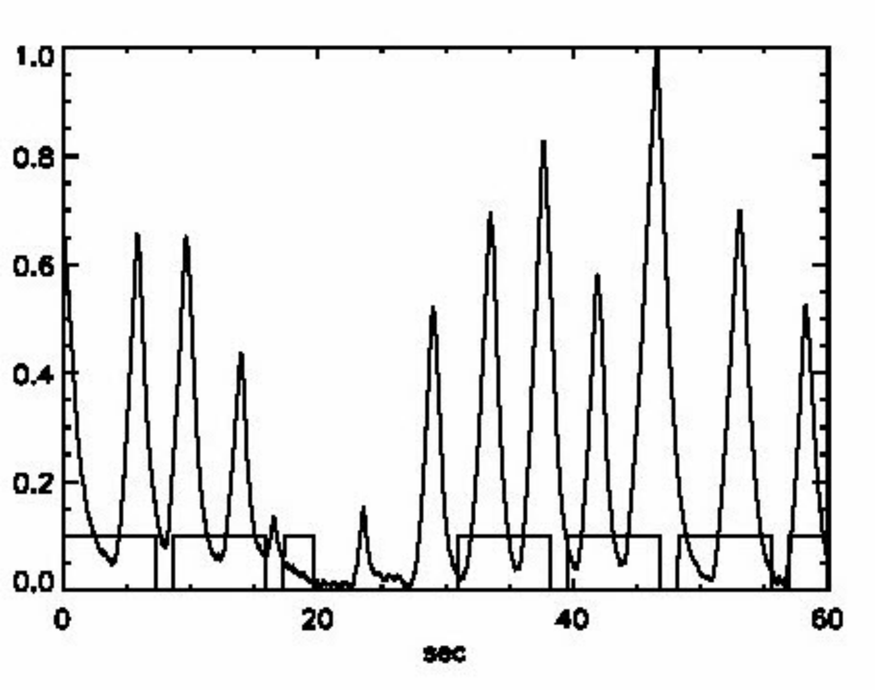
End inspiration

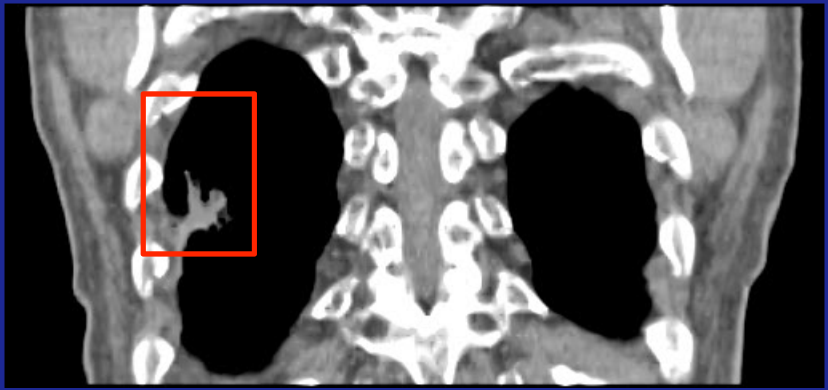


End expiration

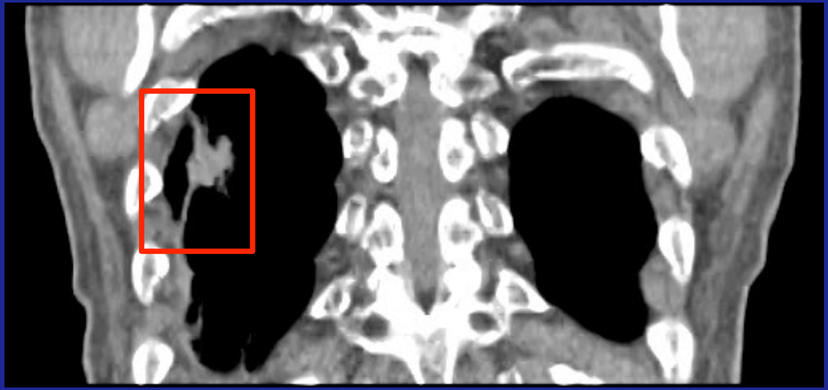
End inspiration with irregular respiration

Prospective 4D-CT (2)

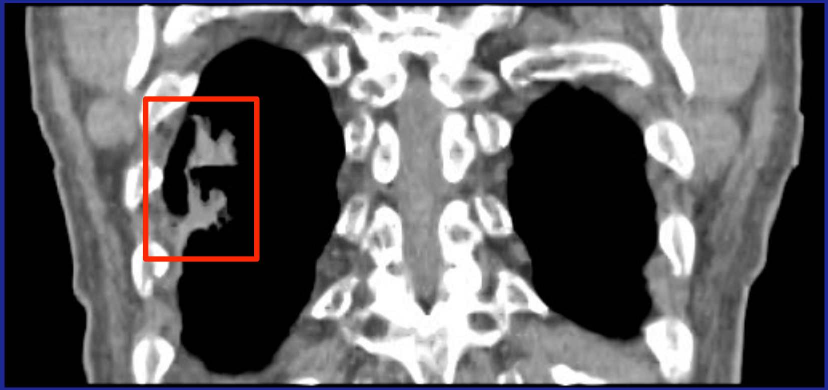




End inspiration



End expiration



End inspiration with irregular respiration

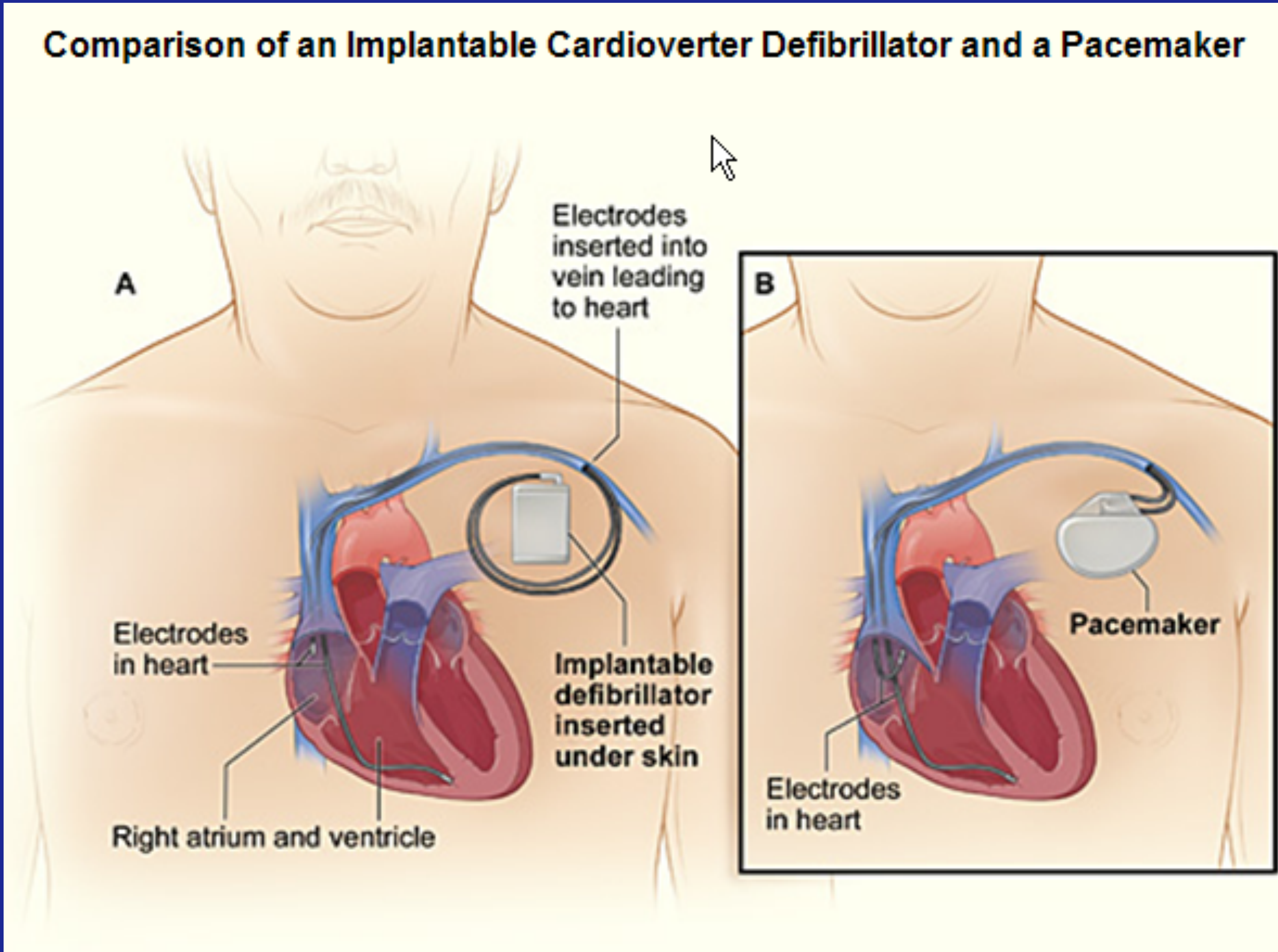
Retrospective reconstruction to remove the images of irregular respiration

Retro	Scan Type	Retro Start	Retro End	No. of Images	Thick (mm)	Interval	Time
Y	Cine Full 0.5 sec.	I40.000	I57.500	96	8 x 2.5	0.500	0.0 6.0
Y	Cine Full 0.5 sec.	I60.000	I77.500	96	8 x 2.5	0.500	0.0 6.0
N	Cine Full 0.5 sec.	I80.000	I97.500	32	8 x 2.5	0.500	0.0 2.1
Y	Cine Full 0.5 sec.	I80.000	I97.500	96	8 x 2.5	0.500	0.0 6.0

Steps of prospect cine 4D-CT

- Stop acquisition when irregular respiration
- Resume acquisition when regular respiration
- Take out incomplete data in retrospective reconstruction
- Repeat as needed
- Not applicable to helical 4D-CT
  - Once the scan is stopped, it can not be resumed.
  - Calculation is needed for the remaining scan.

Radiation and implantable defibrillator and pace maker



http://www.nhlbi.nih.gov/health/dci/Diseases/icd/icd_whatis.html

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Home > Radiation-Emitting Products > Radiation Safety > Electromagnetic Compatibility(EMC)

Electromagnetic Compatibility(EMC)

Interference between CT and Electronic Medical Devices

Effects of X-ray irradiation from CT imaging on Pacemakers and Implantable Cardioverter Defibrillators (ICD) - Literature review

- CT directly irradiating the electronics of ICD can cause electronic interference, the probability that this interference can cause clinically significant adverse events is extremely low.

- The probability of x-ray electromagnetic interference is lower when radiation dose and particularly the radiation dose rate are reduced.

- Interference can be completely avoided when the implantable device is outside of the primary x-ray beam of the CT scanner.

Effects of CT Irradiation on Implantable Cardiac Rhythm Management Devices[1]

Radiology

Cynthia H. McCollough, PhD
Jie Zhang, PhD
Andrew N. Primak, PhD
Wesley J. Clement, BSEE
John R. Buysman, PhD

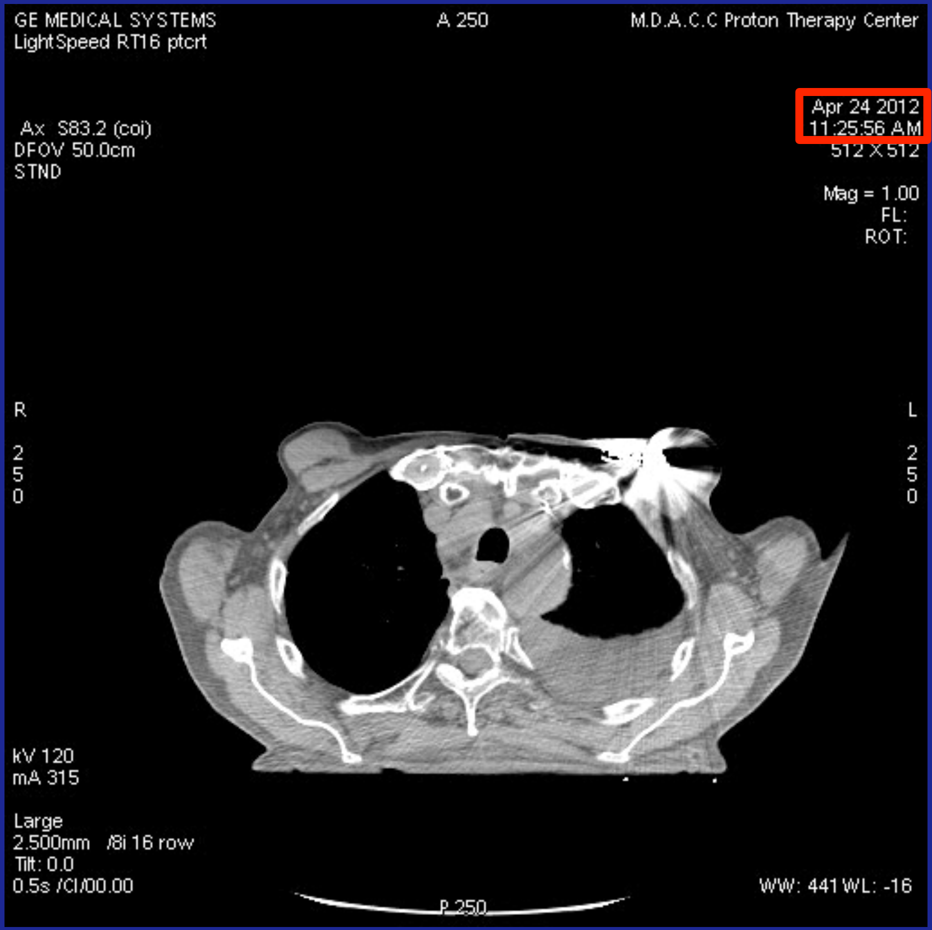
Purpose: To prospectively measure the response of a variety of models of implantable cardiac rhythm management devices (ICRMDs) to the radiation delivered by computed tomography (CT), for both maximum and typical dose levels.

Maximum Dose

Typical Dose

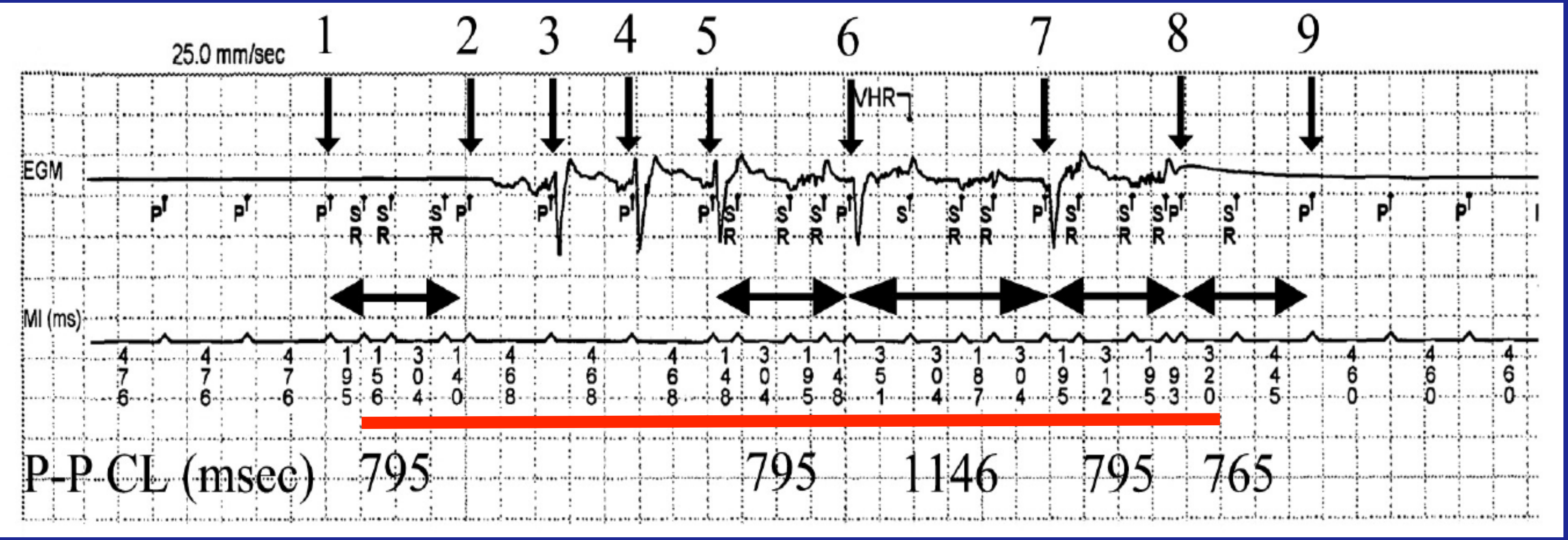
Conclusion: CT irradiation at typical clinical doses results in oversensing of ICRMDs in the majority of devices tested, although the identified effects were predominantly transient.

MDACC 4D-CT patient



23.4 mGy/s dwell time of 5.05 s

First reported 4D-CT induced interference

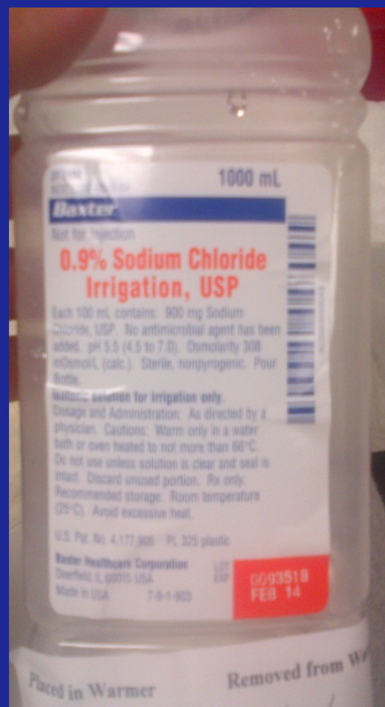


89 year old thyroid cancer patient had a Medtronic Sensia single chamber pacemaker undergoing 4DCT imaging with the cine duration of 5 second per step

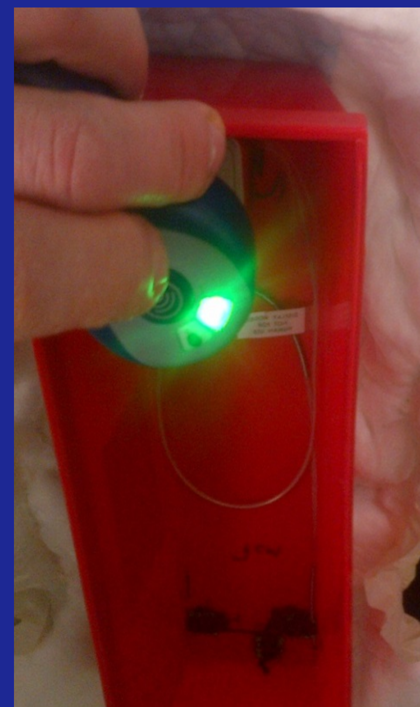
Pan et al, J. Nuc Card, 2018

Experiment setup

Connect the leads to the generator



Saline solution to submerge the PM



Wirelessly-connect PM to computer

Computer (connected to pacemaker) for recording hits or over-sensings


GE MEDICAL SYSTEMS
LightSpeed QX/i CT06_OC0
Ex: 30530
Se: 1 SCOUT
Im: 1
SN
DFOV 50.2cm
S 101
MD Anderson Cancer Ctr 6
narrow beam
zmarc2
Dec 05 2012
11:11:56 AM
888 X 917
Mag = 1.00
FL:
ROT:
Generator
R
2
6
5
L
2
6
5
Az 180
kV 120
mA 10
Leads
WW: 1205WL: 52
I 401

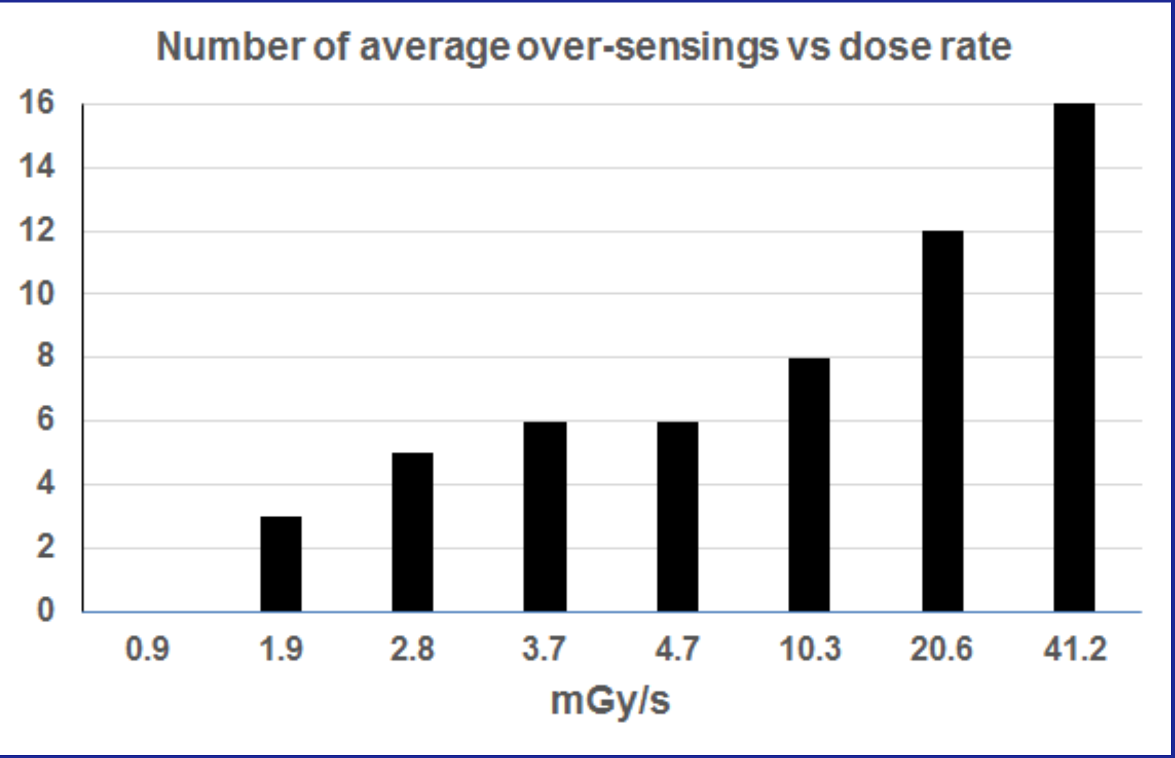

LightSpeed QX/i SYS#CT06_OC0
S 100
MD Anderson Cancer Ctr 6
Ex: 30530
Se: 1 SCOUT
Im: 1
narrow beam
zmarc2
Dec 05 2012
888 x 917
20 mm
R
2
6
5
L
2
6
5
Leads
Oversensing > 1.7 mGy/s
No oversensing = 0.85 mGy/s
kV 120
mA 10
Az 180
11:11:56
W:1205 L:52
I 400

Pacemaker experiment

- Scans of various dose rates at the leads and generator
- Each scan is a 4-s axial scan of 20 mm beam
- Each dose rate was repeated 3 times
- The lowest dose rate was repeated 8 times
- Oversensings were recorded

# Trials	kV	mA	duration (s)	mGy	mGy/s
3	120	440	4	164.8	41.2
3	120	220	4	82.4	20.6
3	120	110	4	41.2	10.3
3	120	50	4	18.7	4.7
3	120	40	4	15.0	3.7
3	120	30	4	11.2	2.8
3	120	20	4	7.5	1.9
8	120	10	4	3.7	0.9

Table 1. Scan techniques and associated radiation dose and dose rates.



Results

41.2 mGy/s

0.9 mGy/s

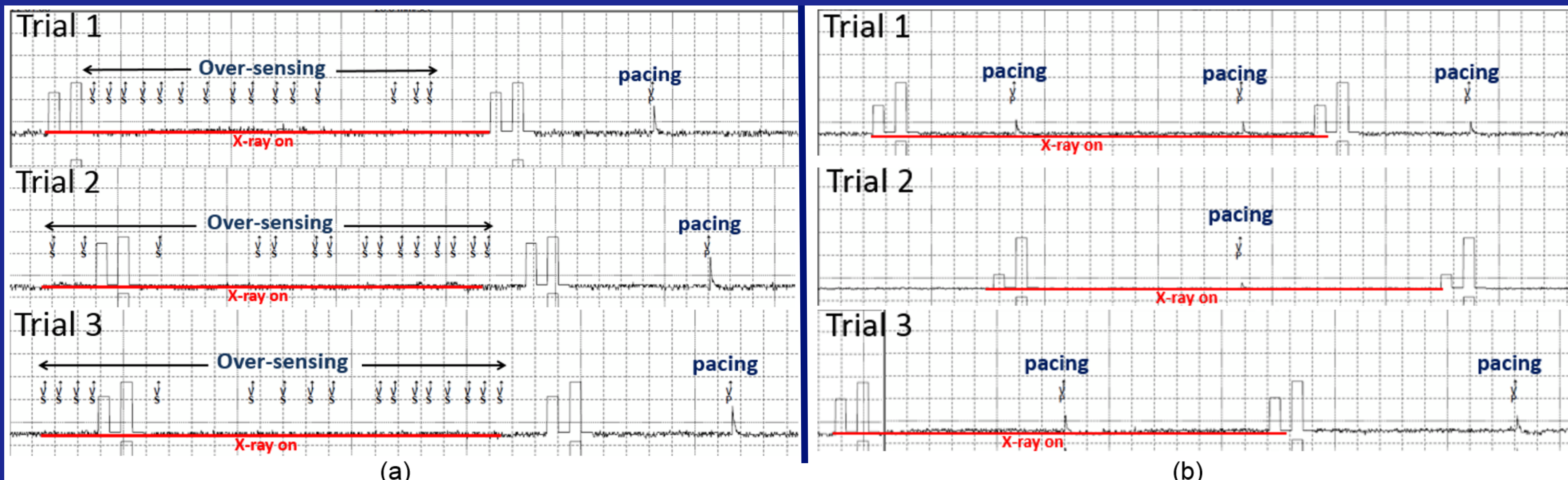


Figure 4 (a) Three trials of the highest radiation dose rate of 41.2 mGy/s for 4 seconds. There were 15, 15 and 17 over-sensings for trials 1, 2 and 3, respectively. (b) First three trials of lowest radiation dose rate of 0.9 mGy/s for 4 seconds. There was no over-sensing in any of the three trials.

The low dose rate of 0.9 mGy/s can be safe for ICD.
This low dose rate is currently used in cardiac PET/CT.

Pan et al, J. Nuc Card, '18

Summary

- 4D-CT is a routine procedure in RT
- Average CT and MIP are useful
- Average CT can improve PET/CT registration.
- Prospective cine 4D-CT can be implemented today to help reduce artifacts
- Most CT scans interfere with the function of pacemaker